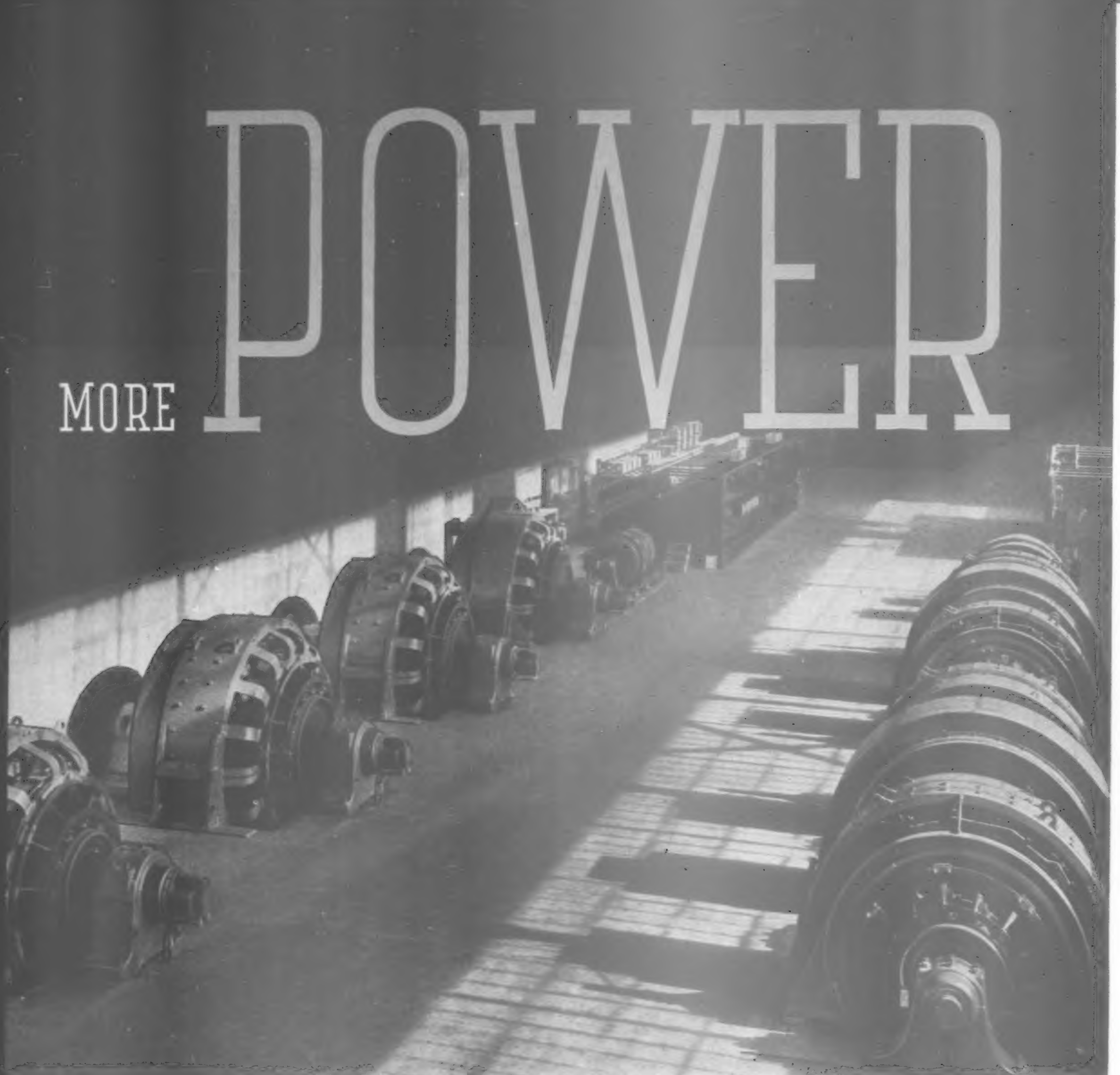
ALLIS-CHALMERS

ELECTRICAL REVIEW

JUNE • 1937



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ELECTRICAL REVIEW

C O N T E N T S

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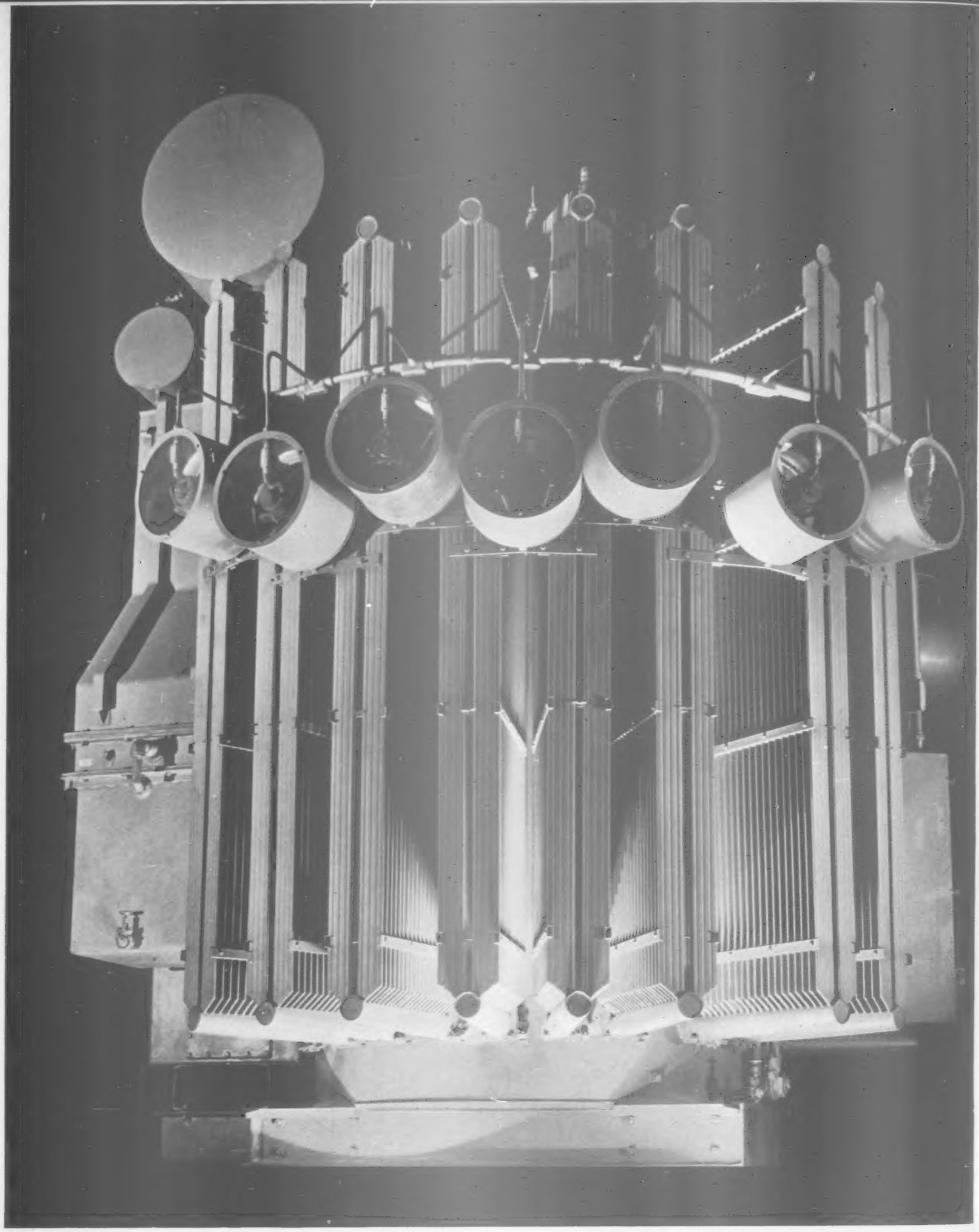


POWER TRANSFORMER

TRENDS IN RAILWAY ELECTRIFICATION

• William Arthur
SPECIAL REPRESENTATIVE . . . ALLIS-CHALMERS MFG. CO.

With the exception of important extensions to the Pennsylvania Railroad's electrified system, there has been, during the past few years, a decided lull in the progress of electrifying the railroads of the United States. The definite trend toward electrification of the past thirty years slowed up during the past six years. It is of interest to study whether or not this slowing up is just a temporary phenomenon or is indicative of a change in trend.

Electrified steam railroads, inclusive of interurban and street railways, use approximately nine billion kilowatt hours yearly, or more than 10 per cent of the total power generated annually in the United States. The trend, therefore, is of interest to all concerned with the electrical industry—manufacturers of electrical apparatus, public utility executives, investors, and consumers large and small.

• Factors causing lapse

The lull in electrification of railroads, during the past six years, can be ascribed to the following three main factors:

1. The slowing up of all business because of the depression.
2. Difficulty of financing major improvements during times of diminishing returns.
3. Improvement in competitive forms of transportation, such as the steam and diesel locomotives, automobiles, trucks, buses, aeroplanes, and pipe lines.

It is obvious that (1) and (2) are temporary factors, whereas (3) is of a more permanent and continuing nature. What is likely for the future?

Before answering this let us summarize some of the more important reasons, which in the past have led to the electrification of our railroads, particularly our main steam railroads. They are as follows:

1. The direct operating economies possible in sections of heavy traffic density.
2. Smoke abatement, permitting safer and quicker terminal and tunnel operations, with indirect advantages, such as increased riding and increase of real estate values along the right of way and near terminals.
3. Effective handling of heavy mountain grade sections, thereby eliminating traffic congestion at critical points.
4. General improvement in passenger and freight services, due to higher possible schedule speeds.
5. Reduction of terminal congestion permitted by multiple unit operation of trains.
6. Increase in track capacity, due to higher speeds; or, what is equally important, deferring the need for additional trackage through acquisition of expensive right of ways.

• What of the future?

Less than 3000 route miles have been so far electrified. This is only a little more than one per cent of the total route mileage of the steam railroads of the United States. It is obvious that from the viewpoint of public welfare there is a real and continuing need for electrification at many points, notably in our big cities, such as Chicago, Boston, Pittsburgh, and others; and it is certain that public pressure will continue to be exerted in the direction of cleaner, faster, and more reliable transportation, which electrified operation permits for both passenger and freight services. Railroads, too, with existing electrified services and increasing traffic densities will find it desirable to extend such services to make existing investments more productive.

Competing forms of transportation, like those that utilize more efficient steam or diesel locomotives, and light weight, high speed streamline trains of the Zephyr type will have limited application in special situations where the traffic densities are too light to justify electrification. These types of equipment, however, are relatively costly in themselves—particularly diesel electric locomotives—and where traffic densities are heavy and growing, as is the case near large terminals, and for heavy passenger and freight services it is more than likely that electrifi-

cation will continue to provide the only adequate answer from the viewpoint of either economic advantage or operating necessity.

In 1936 a group of competent engineers under Government auspices completed an electrification survey which indicated some twenty points in the United States where traffic densities and operating necessities were such that electrification would be desirable and probably economically feasible. The study further showed that these twenty additional electrifications would add 5,429 route miles and approximately 12,000 track miles to those already electrified and five billion kilowatt hours to the yearly power load. Such a large amount of new power would have a stimulating effect on the electrical industry as a whole. On one hand there would be a revenue increase for the utility industries, while on the other the electrical manufacturers would benefit through the resultant demand for new equipment to handle the increased load.

• Purchased power

One of the definite trends during past years has been in the direction of a greater percentage of purchased power. In the early days of electrification, when public utility systems were small as compared to the railroad and its needs, the railroad management often felt it necessary to manufacture its own power in order to insure continuity of service. But today, with large power systems and almost complete interconnection of many large systems, it is seldom desirable and rarely economically advantageous for a railroad to generate its own electric power. Practically all electrifications made in the past ten years use purchased power. This trend will most likely continue.

• Low interest rates

Interest rates on new money are and have for some time been unusually low. Recently a large railroad with good credit was able to finance new equipment

trust certificates on a two per cent basis. This added inducement makes the present a good time to reconsider electrification and, in many instances, might well be the deciding factor.

• Higher speeds, loadings and weight efficiencies

For main line service involving both passenger and freight traffic, the trend is distinctly toward higher speeds and loadings. Speeds of from 90 to 100 miles an hour in passenger service and from 50 to 60 miles in freight service are not uncommon. More powerful locomotives are therefore necessary, requiring larger tractive efforts and greater horse power capacities. But since wheel loadings necessary for adhesion cannot be further increased because of bridge and track limitations, the tendency in electric locomotives is to use more driving axles. That refinement of design has kept pace with growth in capacity is evidenced by the relation of total weights to total horse power capacities. As recently as ten years ago, it was customary for electric locomotives to range from 130 to 140 pounds per horse power of capacity. Today 100 pounds per horse power is available—a gain in weight efficiency of from 30 to 40 per cent in ten years.

In detail electrical apparatus the gain is even greater. The following table gives the pounds per horse power for the traction motors in the cases of three electric locomotives designed at different times for the same service.

Year	1926	1931	1934
Lb per hp	31.3	18.2	14.9

In other words, designers and manufacturers of electrical equipment are continually improving the performance obtained from a pound of copper and a pound of steel or iron. This in itself is applicable to practically all classes of electrical apparatus.

Trends in detail electrical apparatus

1. In electric locomotives and multiple-unit cars, roller bearings are coming into almost universal use, not merely for main axles but for main motor and quill bearings as well.

2. In main traction motors, the tendency is to increase the number of poles and brushholders to the greatest possible maximum. From 16 to 18 poles are now customary, with consequent gain in space utilization.

3. Twin motors of relatively small diameter and high peripheral speed are being employed more and more in the effort to reduce weight and increase capacity.

4. Increased volumes of ventilating air are being used. For instance, where blower motors of 50 horse power have been standard for years on a given locomotive, recent designs for the same unit utilize a 75 horse power motor for ventilating purposes—an increase of 50 per cent.

5. Air blast transformers on electric locomotives and multiple-unit cars are being replaced by oil-insulated types, being less subject to troubles from dust and snowstorms. This improvement has been long overdue.

6. Preventive coils used for transition purposes between notching steps on a-c electric locomotives and multiple-unit cars continue to be utilized in spite of the tendency which such devices have to produce inequalities and surges in the starting tractive effort. By placing supplementary air-core reactors in series with the preventive coils these objectionable features are minimized.

7. On account of the tendency toward longer and hence heavier trains, and consequently more powerful locomotives, extra care is required during starting and acceleration periods. The trend in controllers is toward a greater number of notching points. Additional notches are usually produced by the use of a buck and boost auxiliary transformer, which in a given case triples the number of starting points for the same number of leads out of the main transformer.

Simplification of control systems

One of the most interesting and significant trends is in the direction of still further simplification of control systems through the use of tap changers arranged so that actual current interruption is confined to a relatively small number of contactors—usually only two—leaving the transitional step by step changes to be taken care of by the tap changer itself. The resulting simplification was striking. In the first locomotives arranged in this manner, however, the tap changing and current interruption was provided on the low tension side of the transformer; but experience with this type of apparatus has permitted a still further important advance and one likely to have a profound influence on future electric locomotive designs.

It will be understood that increasing locomotive capacities necessitated extremely large cables and switchgear to handle the heavy currents of such locomotives, so much so that hardly any room was left on the locomotive for efficient inspection facilities. In addition such heavy cabling and switchgear are relatively expensive and costly to maintain. To obviate these difficulties, and as a natural development of the tap changer scheme referred to, the most powerful electric locomotives of recent years have used the tap changer idea applying it to the high tension side of the transformer. Several such locomotives of more than 8000 horse power capacity each have now been in service for a sufficient length of time to demonstrate thoroughly the value of this plan. The tap changer itself is a comparatively small piece of apparatus incorporated in the main transformer itself. All of the usual heavy cabling and switchgear is eliminated, so that even on such powerful locomotives there is ample room everywhere for proper inspection. This trend toward simplification will no doubt continue.

Future looks promising

Low interest rates for capital; rising prices for labor and material; inflationary tendencies in the value of the dollar; increasing volume of general business; improved designs; elimination of need for a railroad to undertake heavy capital investment in power plants; public pressure for higher transportation speeds and improved facilities; operating necessities such as terminal congestions and difficult grades, smoke elimination—all of these and many others are factors tending to bring about electrification. It would not be surprising to see a marked revival of interest and many new electrifications started or extended in the near future.

GENERAL PURPOSE SQUIRREL CAGE INDUCTION MOTORS

• J. M. Hillman

NORWOOD WORKS . . . ALLIS-CHALMERS MFG. CO.

Many readers can recall the time when practically the only squirrel cage motor available was what is now known as the normal torque normal starting current type. Full voltage starting in ratings over five horsepower was viewed askance. High starting torque demanded a wound rotor motor, and the low starting current type was an unknown entity. Naturally this resulted in a decided limit in the scope of application, but the inherent advantages of simplicity of construction, low first cost, and economical operating and maintenance expense, were features too attractive to be denied; and as generating capacities increased and voltage regulation improved, six types of squirrel cage motors were developed and standardized to broaden the range of application almost without limit.

The table on page 10 defines these various types, outlines briefly their comparative characteristics, and lists their principal permissible applications. All types have been evolved through more or less simple design changes from the original basic squirrel cage motor, thereby preserving its mechanical advantages and penalizing price and performance in a remarkably small degree.

Each class has a speed-torque characteristic peculiar to that group. In fact, neglecting such considerations as efficiency and power factor, which are secondary so far as application is concerned, the speed-torque characteristic is a measure of the ability of a motor to perform a specific duty, for it discloses the four major requirements necessary for the selection of the correct type of motor. These requirements are as follows:

1. The motor must be capable of starting the load from rest.
2. Acceleration to full speed must be attained without injury to motor or load.
3. Full load must be carried in accordance with the required duty cycle.
4. Capacity should be available for periodic or accidental overloads.

Definition	NEMA Classification	HP Range	GENERAL CHARACTERISTICS: Starting Torque	Breakdown Torque	Starting Current	Efficiency	Power Factor	Slip	TYPICAL APPLICATIONS
Normal Torque Normal Starting Current.	A	½ to 200	* Varies according to number of poles.	Not less than 200% of full load torque.	500 to 1000% of full load current. Varies with size of motor, number of poles and voltage.	Relatively high, even at fractional loads. Increases with speed and size of motor.	Relatively high at full load. Decreases rapidly with decrease in load. Increases with speed and size of motor.	3 to 5%	Blowers. Fans. Line Shafts. Machine Tools—Boring Mills, Broaching Machines, Drills, Grinders, Lathes, Milling Machines, Metal Saws, Shapers, Screw Machines. Pumps—Centrifugal. Wood Working Machines—Circular Saws, Lathes, Planers, Moulders, Tenoners.
Normal Torque Low Starting Current.	B	7½ to 200	Approximately the same as Class A.	Same as Class A.	‡	Same as Class A.	Somewhat lower than Class A.	1½ to 5%	Same as Class A.
High Torque Low Starting Current.	C	1 to 200	225% of full load torque.	Not less than 200% of full load torque.	Approximately the same as Class B.	Lower than Class A.	Lower than Class B.	3 to 7%	Ball Mills. Compressors. Conveyors. Crushers. Pumps—Displacement.
High Slip.	D	1 to 50	250% of full load torque.	250% of full load torque.	300 to 500% of full load current.	Relatively low.	Relatively low.	12 to 16%	Cranes. Elevators. Hoists.
Medium Slip.	D	1 to 5 12	300 to 400% of full load torque.	300 to 400% of full load torque.	400 to 800% of full load current.	Relatively low.	Relatively low.	7 to 11%	Bull Dozers. Punch Presses. Shears.
Low Starting Torque, Normal Starting Current.	E	50 to 200	Not less than 50% of full load torque.	Not less than 150% of full load torque.	Same as Class A.	Comparable to Class A.	Comparable to Class A.	1 to 3½%	Centrifugal Pumps and Fans.
Low Starting Torque, Low Starting Current.	F	40 to 200	Not less than 50% of full load torque.	Not less than 150% of full load torque.	350 to 550% of full load current.	Comparable to Class A.	Comparable to Class B.	1 to 3½%	Same as Class E.

*Starting torques in per cent of full load torque applying to ratings for belted service are not less than the following:—

No. of Poles	Starting Torque	No. of Poles	Starting Torque
2	150%	10	120%
4	150%	12	115%
6	135%	14	110%
8	125%	16	105%

Ratings recommended for direct connection only generally fall within classifications E and F.

‡Locked rotor values of starting current in amperes do not exceed the values given in the following tabulation:—

HP	220 volts		440 volts		550 volts	
	3 ph	2 ph	3 ph	2 ph	3 ph	2 ph
7½	115.	98.6	58.	50.	46.	40.
10	141.	123.	70.5	61.5	56.	49.2
15	197.	171.	98.5	85.5	78.6	68.4
20	251.	222.	125.	111.	101.	89.
25	304.	270.	152.	135.	122.	108.
30	360.	320.	180.	160.	144.	126.

For ratings larger than 30 hp, starting currents of Class B motors will not exceed approximately 500% of full load current on 220, 440 and 550 volt motors and 550% on 2200 volt motors.

Speed-torque curves of the various classes are shown in the diagram on page 11. All solid curves are on the basis of full voltage being applied to the motor terminals. The dotted curves show the effect of reduced voltage starting on Class A motors; all other classes being generally started on full voltage. For simplicity, torques are plotted in terms of per cent of full load torque; conversion to pounds can readily be made from the formula

$$T \text{ (torque in lb ft)} = \frac{\text{hp} \times 5250}{\text{(full load) rpm}}$$

No study of squirrel cage motor characteristics would be complete without consideration of its most serious handicap—the inherently high starting current. While it is possible to obtain a cage type motor with a starting torque as high as any other type of electric motor, the fact remains that for a given starting torque, the starting current of a squirrel cage motor is several times greater than that of a wound rotor or direct current motor of the same rating. Comment on this feature is, therefore, included in the discussion of the various classes of motors which follows.

• Class A motors

Class A motors, as their definition indicates, have normal torque and normal starting current. The starting torque depends on the number of poles—decreasing as the poles increase. The speed torque curve of the rating selected in the diagram on page 11 shows this torque as 135% of full load torque on full voltage starting. When started on reduced voltage, this torque is decreased in the ratio of the square of the per cent of applied voltage. For example, starting on an 84% compensator tap reduces the torque to 0.84^2 (approximately 70%) of 135%, or about 95% of full load torque.

The breakdown or pull-out torque, through which point the motor passes in coming up to speed, is exceeded only by the Class D motor. This not only assists in producing a high average accelerating torque but is an indication of the heavy overloads which this motor is capable of carrying. In this connection, these overloads are accompanied with but relatively little drop in speed, for even under the maximum load which the motor can handle, which is

well over 200% of full load, the speed is approximately 80% of synchronous. Loads between full and maximum produce correspondingly lower decreases in speed. Class A motors, however, should not be subjected to sustained overloads, if overheating of the motor is to be avoided.

Starting currents of Class A motors vary with the horsepower, speed and voltage. Generally speaking, the larger the horsepower and the higher the speed, the greater will be the starting current; also, 2200 volt and higher voltage motors will have higher starting currents than motors wound for commercial voltages of 550 and below. As indicated in the table, this spread ranges from 500 to 1000% of full load current, and reduction is obtained only by reducing the voltage on starting. This may be accomplished either by means of transformer or resistance type starters, and at a sacrifice of starting torque.

The standardization of normal torques and unrestricted starting currents applying to Class A motors provide the necessary latitude for incorporating a performance standard against which all other types are measured. This unit is, furthermore, the lowest priced of all continuous rated motors; and since practically all motor manufacturers now build all general purpose ratings in this class suitable for starting on full voltage, it is recommended for all applications where its starting and accelerating torques are adequate and where its starting current does not exceed the permissible limit.

• Class B motors

Class B motors sacrifice both power factor and breakdown torque to obtain the advantage of low starting current. As a result of the lower breakdown torque, the average accelerating torque is correspondingly lower. Its use is recommended, therefore, only in cases where the starting current limitation imposed by the power supply prohibits the Class A motor.

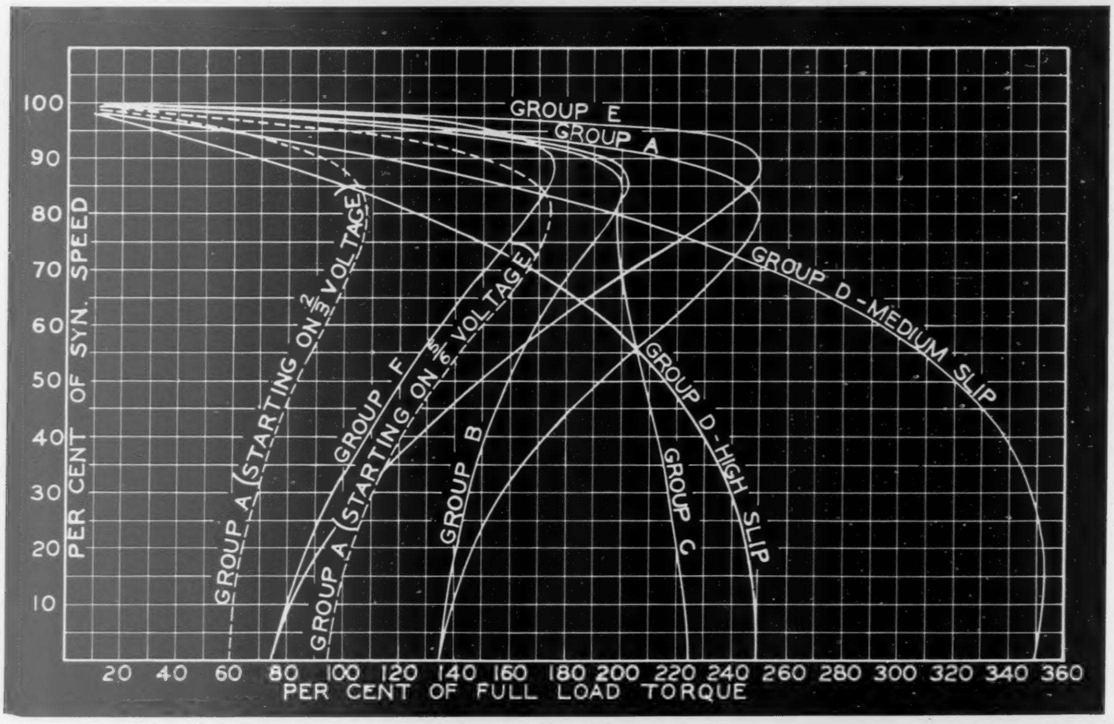
• Class C motors

Class C motors, more readily recognized by many as double cage motors, have speed torque characteristics which make this type particularly adaptable to loads having an excess of friction in starting. Conveyors whose friction load may increase considerably during cold weather and compressors without unloading devices are outstanding examples.

The starting torque of Class C motors is at least 200% of full load regardless of the number of poles. The speed-torque curve in the diagram is, therefore, typical for any speed, and a peculiarity which must not be overlooked in this type is the value of breakdown or pull-out torque which is lower than the starting torque. In other words, these motors do not have the short time overload capacity of the Class A motor, and in addition sacrifice both efficiency and power factor.

Besides its high starting torque advantage, the Class C motor has an inherently low starting current,

Speed Torque Curves: 50 hp, 440 volt, three phase, 60 cycle, 1200 rpm (Synchronous Speed)



comparable, in fact, to Class B; and, therefore, while it is in general a line-start motor, a combination of starting torque requirements and starting current limitation might be such that those conditions could be satisfied by the Class C motor with reduced voltage starting rather than resorting to a wound rotor motor. For example, assume a load requiring a 40 hp, 1800 rpm, 3 phase, 60 cycle, 440 volt motor with a starting torque requirement of 150% of full load torque and where the power supply limits the starting current to a value not exceeding 350% of full load current. The Class A or B would be suitable so far as starting torque is concerned, but both would exceed the starting current limitation. The Class C motor, however, started on an 84% compensator tap, would satisfy both conditions.

• Class D motors

Class D motors are similar to Class C motors in that they exert their maximum torque at the instant of starting. This, however, is the only point of similarity, for in all other respects they differ from this and the other classes of squirrel cage motors. It will be noticed from their speed-torque curves that there are two types of Class D motors, one whose curve passes through full load at about 85% of synchronous speed, the other at about 91% of synchronous speed. The former is commonly designated as a "high slip" motor, usually intermittent rated, the latter "medium slip" and usually continuous rated.

High slip Class D intermittent rated motors are applied principally on cranes, hoists, elevators, etc. It has been established empirically that the torque required to start such apparatus is approximately 250% of the power required to maintain full speed under full loaded conditions. Accordingly, these motors have a starting torque of approximately 250% of full load, and the torque curve falls off rather rapidly as acceleration is accomplished. High slip motors for elevator service are "quiet operating"; design restrictions in this respect are not imposed on motors of this type when used on other applications.

Medium slip motors have the highest starting torque of all classes. As a result of this high starting torque, the average accelerating torque is also high, for which reason this type has particular application to flywheel loads. In fact, this motor is known by many only as a "punch press" motor, since a punch press is the most common type of load which utilizes a flywheel as an inherent item in its assembly. The necessity for high accelerating torque on flywheel, or high inertia—loads is apparent from the formula:

$$T \text{ (torque in lb ft)} = \frac{WR^2 \times \text{rpm}}{307 \times t}$$

in which W = weight of the mass to be accelerated
R = its radius of gyration
t = time for acceleration in seconds

From this formula it can be seen that if the rating of Class D motor selected accelerates the load in a given time (t), any other class of motor of the same rating will require a longer accelerating period since the torque (T) is less. A hazard, therefore, in applying another class of motor to loads of high WR^2 lies in the fact that the prolonged accelerating period with the attendant high current might result in over-taxing the thermal capacity of the motor, causing shortened life, if not complete motor failure.

The slip of these motors on loads which depend on flywheels for successful operation is also an important consideration. This slip being relatively high enables the motor to pick up the load when the excess energy stored in the flywheel has been released during the working stroke of the machine. When the working stroke is completed the load is decreased, enabling the motor to re-accelerate the flywheel to full speed and restoring energy to it. The supplying and releasing of power in this manner tends to smooth out the load peaks, thereby decreasing the maximum power demand to a level comparing favorably with normal torque motors of equivalent horsepower rating.

Class D motors obtain their high torque feature by means of high resistance rotor cages. This means high rotor losses and, therefore, sacrifice in efficiency. Power factor is also sacrificed, but starting currents are low, particularly in the high slip motors. Speed-torque characteristics are very susceptible to minor design changes, and special applications requiring motors of this type should be accommodated by motors "custom built" to meet their particular requirements.

• Class E and F motors

Class E and F motors are confined to high speed ratings which are considered suitable only for direct connection and are applicable only to low torque drives such as fans and centrifugal pumps. As indicated in the speed-torque curves, both starting and breakdown torques are low, but this sacrifice in torque permits designs incorporating better efficiency and speed regulation. The major difference between Classes E and F is the lower starting current of the latter type.

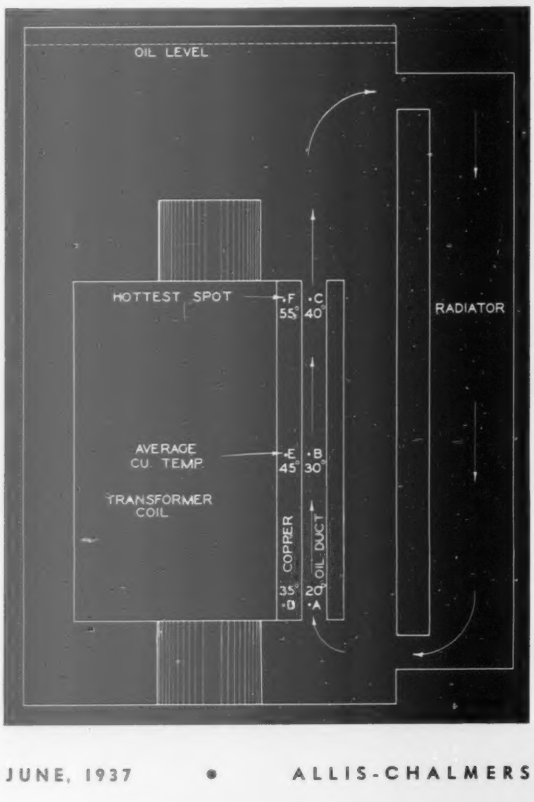
Obviously, a discussion of characteristics of such a wide range of ratings and speeds as are included in the general purpose sizes of induction motors must be confined to generalities. However, the essential differentials, in the various classes as outlined above, furnish a working basis to assist materially in selecting the type of motor best suited for a given application.

ENGINEERING FUNDAMENTALS

HOT SPOT TEMPERATURE OF TRANSFORMERS

The limitation of the load a transformer can safely carry is set by the temperature of the hottest spot, which should not exceed a safe value. In a modern transformer the principal reason certain parts are at higher temperature than others is because of the variations in the oil temperature in various portions of the transformer.

The oil in a transformer circulates as shown in the diagram. The oil absorbs heat from the coils as it flows upward through the oil duct. Typical values of oil temperature are shown at A, B, and C. For example, the oil at the bottom of the duct at point A has a temperature of 20° C, while at the top of the duct it has a temperature of 40°C. A temperature difference between the copper of the winding and the oil which is closest to the copper is necessary in a transformer so that heat will flow through the insulation and the boundary surface to the oil. If the winding is uniform, this temperature difference between the copper and the nearest oil will be constant throughout the winding. In the example shown this temperature difference is 15° and is the true gradient of the transformer. This value of true gradient varies directly with the amount of heat generated in the copper; consequently, the true gradient is proportional to the square of the load.



The copper temperature at any point may be obtained by adding the true gradient to the oil temperature at the nearest point. The temperatures at the points D, E, and F are obtained in this manner by adding 15° to the temperature of the nearest oil. In the diagram the hottest spot temperature is equal to the hottest oil plus 15° which is equal to 55°. When the temperature of a winding is obtained by resistance, the temperature obtained is the average copper temperature, which is obviously 45° for this example.

The difference between the hottest spot temperature and the average copper temperature is called the hot spot allowance. In this example the correct hot spot allowance is 55° minus 45°, or 10°. This happens to be the same as the conventional 10° allowance given in the A.I.E.E. standards.

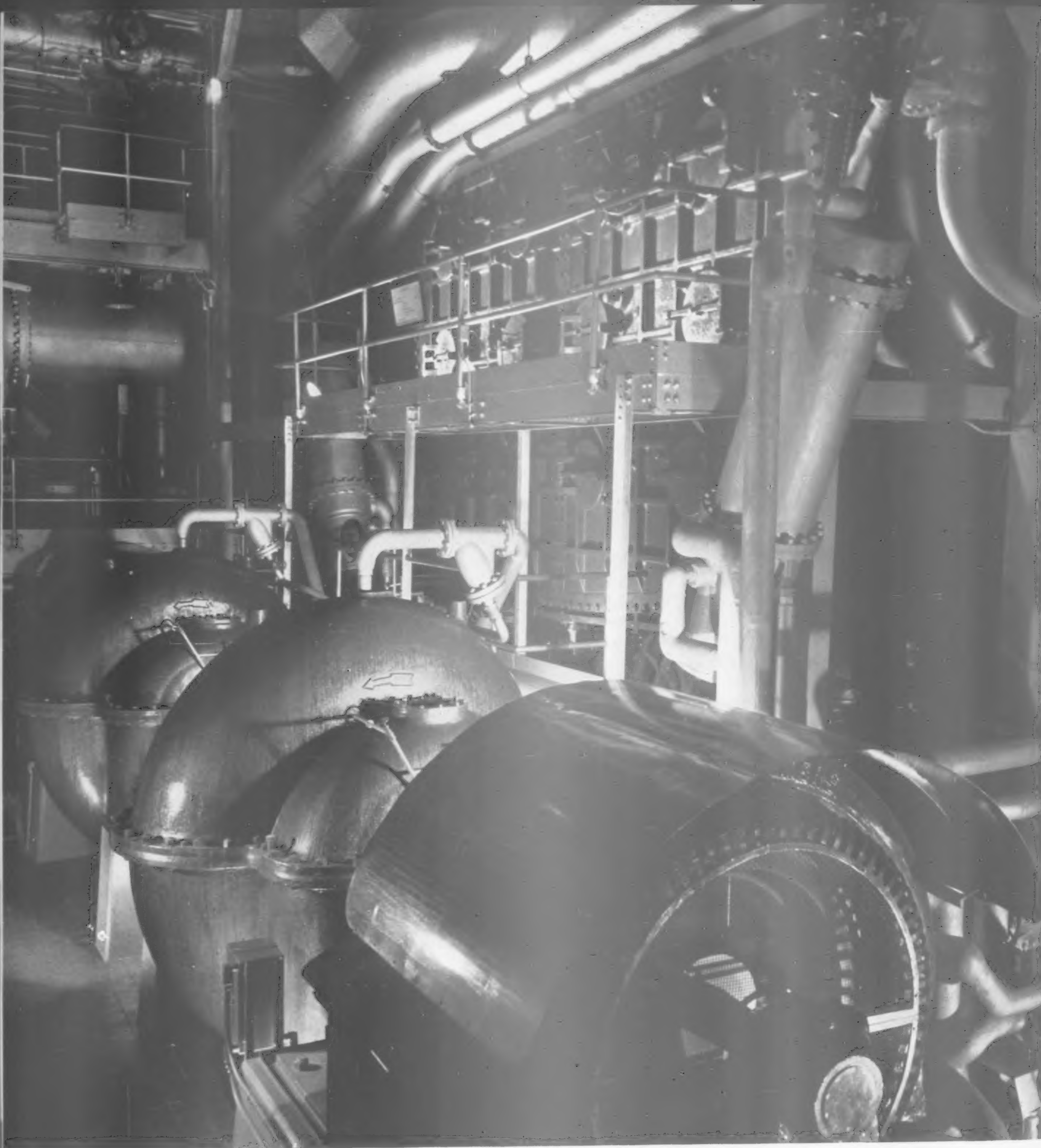
It is difficult to measure the hot spot temperature of a transformer winding directly, and hence it is usually obtained indirectly. The temperature of the hot oil of a transformer is easily obtained by means of a thermometer in the top oil. The hot spot temperature of the copper is equal to the temperature of the hottest oil plus the true gradient at the load being carried on the transformer. The true gradient at full load is equal to the tested gradient at full load plus the hot spot allowance. If the hot spot allowance at full load is taken from the A.I.E.E. standards as 10° C, the hot spot temperature is equal to the hot oil temperature plus the load squared times "the tested gradient plus 10°C", that is

$$T = T_0 + L^2G$$

Where T is the hot spot temperature

- T_0 is the oil temperature
- L is the ratio of the load being carried to full load
- G is the true gradient at full load, which is assumed equal to "tested gradient plus 10°C."

Temperature indicators which read oil temperature plus the load squared times "the tested gradient plus 10° C" are a common means of obtaining the hot spot temperature. Another common means is by calculation of the oil temperature and the tested gradient using the above equation.



PORT WASHINGTON CONDENSER AND PUMPS

PROTECTING NEW INVENTIONS

• Leo Teplow

PATENT ATTORNEY . . . ALLIS-CHALMERS MFG. CO.

Tragic is the tale of the poor, hardworking inventor whose revolutionary invention is stolen by an unscrupulous villain who obtains a patent for the invention and makes a fortune from it. Far be it from me to destroy so satisfactorily heartbreaking a picture. But it is unfortunate that the oft-told tale has so inspired inventors with a fear lest their inventions be stolen that the inventions are sometimes lost through too much caution.

What is the best way to protect an invention on which no patent has been obtained? What to do with an invention before an application for patent has been filed? Is keeping an invention secret the best protection? These questions frequently occur to the inventor, and visions of the defrauded inventor may result in the practice of such complete secrecy that the inventor may never be able thereafter to find any one to corroborate his own statements as to the dates of conception or reduction to practice of the invention. The following are a few suggestions which may help the inventor not only to prevent the theft of his invention, but to preserve his rights in subsequent litigation.

• Write it down

1. When you conceive an invention, *write it down.* If possible, make a sketch to show the principle on which the new invention operates and one or two modifications. Write in at least enough description to make the sketch comprehensible. *Sign and date each sheet* on which the invention is disclosed. If it is ever necessary to add anything to these original disclosures, use a different color of ink, and initial and date the additions or alterations so that it will be possible to determine the nature and date of the original invention and of subsequent alterations or additions.

"But if I put my invention down on paper, some one may see it and claim it for his own." Possible, but not likely, if you take the next step, discussed below. But the importance of putting your invention down on paper cannot be overemphasized. The human memory is an unreliable guide. Prompted by numerous suggestions, we may "remember" things we never knew. It is hard to distinguish between that which we remember and that which we have recently learned. Moreover, how can one prove exactly what the invention was, unless one can point to a description made at the time?

• Get a witness

2. Get someone to *witness your sketches and description.* At least two witnesses are preferable. If possible, explain your invention to these witnesses, and have them sign your sketches as follows:

"Witnessed and understood
(Signed) A. B. Cook
June 3, 1937.
(Signed) D. E. Fort
June 3, 1937."

"But," you object, "if I explain my invention to others, what is to keep them from stealing it?"

The surest guarantee that your witnesses will not steal your invention is their signature as witnesses to your invention. If the question of priority of invention between you and your witnesses ever arises, their signatures *as witnesses to your invention* are the best possible proof that they believed that you were the inventor at the time they witnessed your sketches.

It is of the utmost importance to illustrate your invention, to explain it to others, and to have the illustration witnessed. It is very difficult and frequently impossible to prove the date when you made your invention, unless you can produce documentary evidence in the nature of sketches, written description, correspondence, working drawings, etc. And when such documentary evidence is available, its value is greatly enhanced if it can be identified by witnesses.

• Perfect it

3. Keep actively at work perfecting your invention until you either (a) file an application for patent on it; or (b) obtain a working model or full sized machine to prove that the invention is successfully operative, and test it before witnesses. If you have a brilliant

idea, and put it on the shelf for a couple of years until you have more time to spend on it, another inventor may come along after you, conceive the same idea, and by working diligently to reduce it to practice and perhaps put it on the market, be legally adjudged to be *the first inventor*. This is because invention is more than cerebral pyrotechnics. Invention consists of the two steps of (1) conceiving the solution to a problem (frequently preceded by a realization of what the problem is, which may be an important step in obtaining the solution); and (2) making a model or full size machine (or other article) in accordance with the conception and operating it in the way it is intended to operate in actual use. In technical jargon this second step is termed "reduction to practice." Conception and reduction to practice *together* constitute invention. To put it arithmetically,

Conception+Reduction to Practice=Invention.

• Strive to reduce it to practice

Therefore, if you have conceived an invention but have not reduced it to practice, you have not technically made an invention at all. If, while your conception is lying on the shelf, so to speak, another inventor comes along with the same idea and diligently goes to work to reduce it to practice, and makes a working model of it before you get around to developing your brain-child, the other fellow is regarded as being the first inventor. Therefore, it is important to keep actively developing your invention and not to let it lie dormant after conception. For if you are *diligent* in attempting to reduce your invention to practice, a later inventor is not entitled to a patent even if he completes it before you do.

In order to encourage inventors who may not have the time or money to reduce an invention to practice, the law considers that an inventor who files an application for patent has made a "constructive" reduction to practice. The word "constructive" as used in law indicates that the thing to which it is applied is a legal fiction, and for legal purposes will be regarded as fact. So in this case, the filing of a complete application for patent is regarded as a "constructive" reduction to practice, although every one knows that a patent application is not a working model. Therefore, a man who invents an improved tractor does not need to build a tractor or even a model of a tractor in order to complete his invention; he may simply instruct a patent attorney to prepare a patent application, and if there has been no lack of diligence between the time that the invention was conceived and the date of filing a complete application therefor, the inventor's rights are preserved.

There are many and conflicting decisions as to what constitutes "due diligence" required of an inventor to maintain his priority rights, but it is beyond the scope of this article to go into that. Suffice it to say that an inventor who conceives an invention should diligently strive to reduce it to practice or to file a patent application covering it, in order to protect his inventor's rights.

Of course, it is possible that the inventor may be so poor that he has neither the means to embody his invention in an operative model nor the funds to pay an attorney's fees for a patent application. He may then file an application himself, without the aid of an attorney, but the preparation and prosecution of patent applications is so highly technical a matter that an inexperienced inventor is not likely to get adequate patent protection without competent legal advice; and there would still remain the problem of paying the filing fee and the final fee, should the application mature to patent.

The problem of an inventor who cannot raise enough funds even to meet the filing fees remains unsolved. As with all other legal rights, the rights of an inventor are applicable to rich and poor alike; but a certain minimum amount of money is essential to set the wheels of law in motion to enforce those rights.

• Secrecy is dangerous

From the above preliminary discussion, it should be clear that to surround an invention in secrecy is a risky matter which may result in loss to the inventor; and that the safest steps to take to protect the inventor's rights are: 1. To make a sketch and written description of the invention, signed and dated; 2. To have the sketches and description witnessed (signed and dated by two or more witnesses); and 3. To continue diligently developing the invention until an application for patent has been filed thereon, or until the invention has been embodied in a successfully operative structure, and its operation witnessed by others.

Like miserliness with wealth, shrouding an invention in secrecy is likely to defeat its own ends.

PORT WASHINGTON

• C. C. Jordan, Assistant Manager
STEAM TURBINE DEPT. . . . ALLIS-CHALMERS MFG. CO.

Port Washington to informed engineers signifies the most efficent steam power plant in operation today. In the design of this station The Milwaukee Electric Railway and Light Company naturally used their design and operating experiences gained at their Lakeside station. Careful, detailed studies were made to determine what improvements were necessary to give the maximum efficiency without impairing reliability or flexibility. The most important improvements consisted of the unit-design and the use of 825°F steam temperature for both throttle and reheat steam. The unit design involved the purchase of one 80,000 kw turbine and one 690,000 lb per hr bent tube type boiler with combination radiant and convection type superheater and radiant type reheater. Although construction work was started on the Port Washington Station in 1930 it was not put into operation until November, 1935.

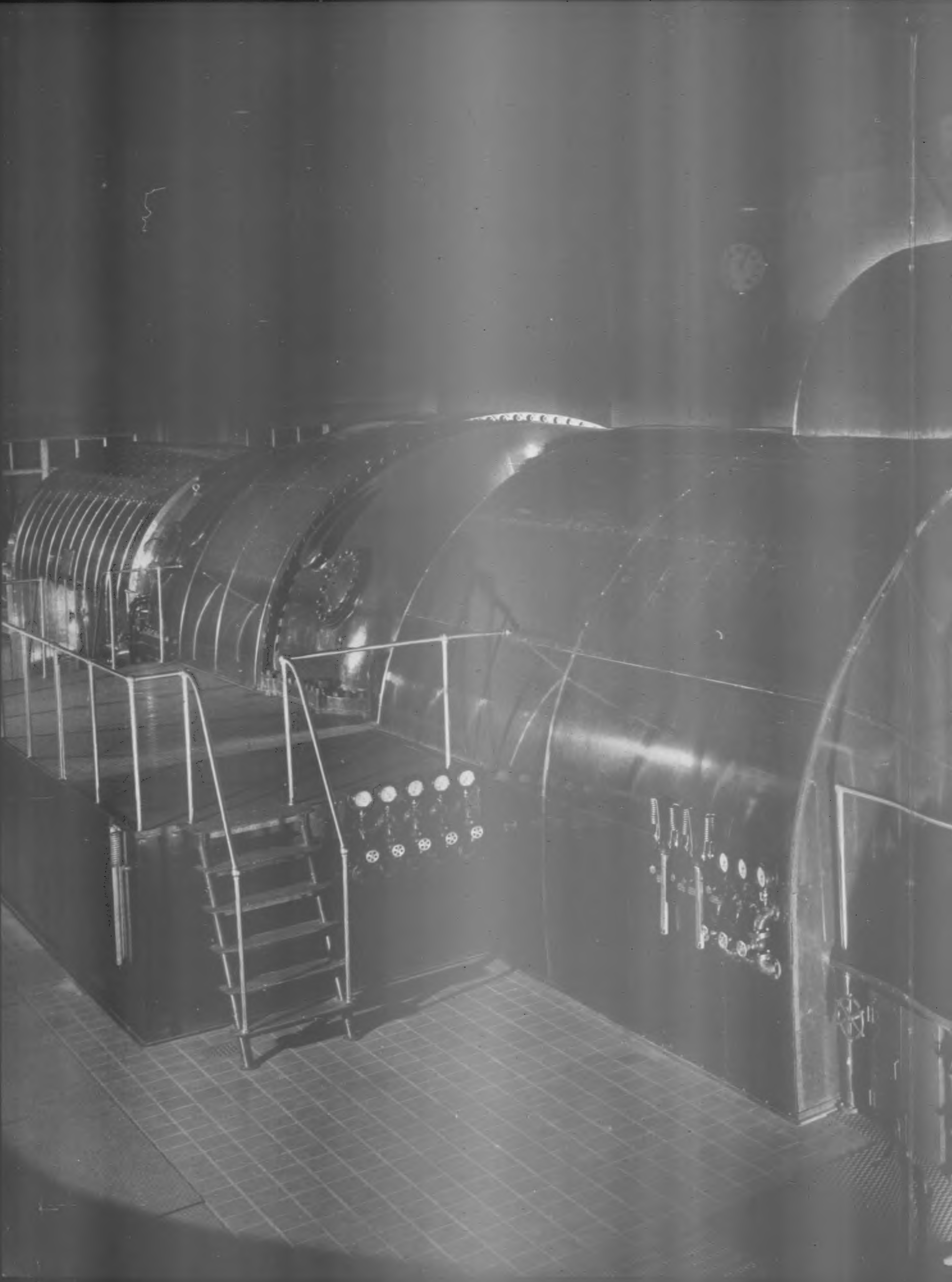
The overall net heat rate of less than 11,000 Btu per kw hour obtained by this station as shown by various published reports indicates that the engineering done by The Milwaukee Electric Railway and Light Company on this station was fundamentally sound so far as efficiency is concerned. In his paper on the Port Washington station, presented at the 1936 Annual Meeting of The American Society of Mechanical Engineers, Mr. F. L. Dornbrook, Chief Engineer of Power Plants of The Milwaukee Electric Railway and Light Company reports that "the outages so far experienced (10½ months operation) have been for the most part due to load conditions rather than to operating difficulties. The boiler and turbine have performed with equally high reliability." He further reports that "a load of 15,000 kw was, on a few occasions, carried for several hours and a load of 20,000 kw for many hours. After the thirty hour week-end shutdowns of April and May 1936, due to lack of load, the turbine unit was usually synchronized within 45 minutes after warming was started." Thus it would appear that reliability and flexibility were not sacrificed to obtain the record-breaking efficiency results.

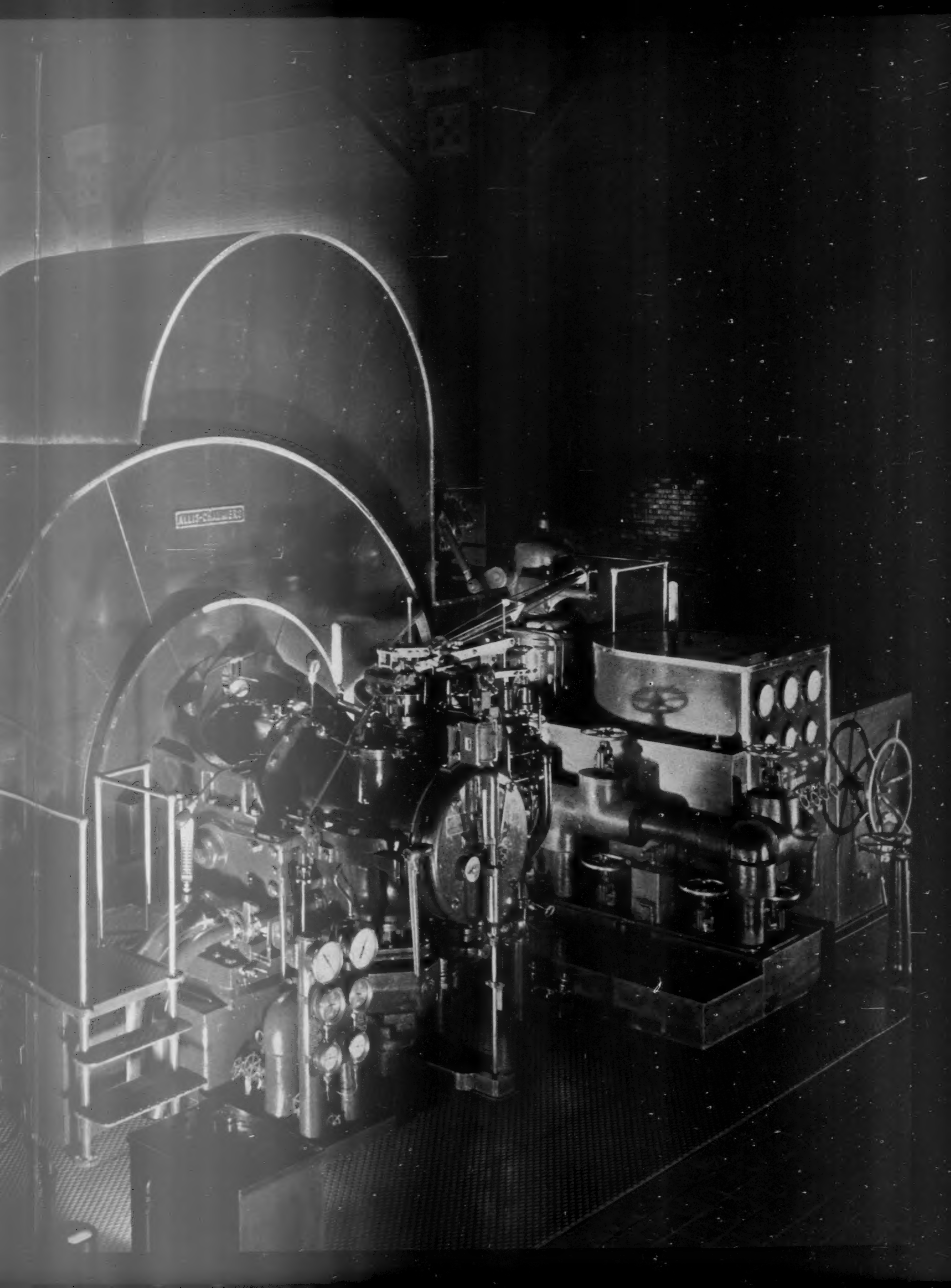
The turbo-generator is an 80,000 kw tandem compound unit. The turbine is designed for normal operating steam conditions of 1230 lb gage throttle pressure, 825°F throttle steam temperature, 825°F reheat steam temperature, and one inch absolute exhaust pressure. The turbine is of the tandem compound reaction type driving a single generator. After partial expansion in the high pressure turbine cylinder, the steam is withdrawn and reheated to 825°F in the reheater. It is then admitted to the high pressure cylinder again behind a diaphragm which divides the cylinder between the outlet nozzle to the reheater and the inlet nozzle from the reheater. The low pressure turbine is of the opposed double flow type, thus providing large exhaust blade area to take full advantage of the low exhaust pressure which prevails at Port Washington over a large part of the year. In the design of the blading, the valves and the steam paths in the turbine every care was taken to insure high efficiency. In his paper Mr. Dornbrook reports turbine stage efficiencies of about 84 per cent computed from stage pressure and temperature readings and checked by weighed water tests.

On a turbine of this type continuity of service is of great importance. This has been obtained at Port Washington by careful attention to design details. A new type of cylinder flange construction, a symmetrical cylinder casing design, admission of high temperature steam to both the upper and lower halves of the cylinder simultaneously, and a cylinder support design that is correct in every detail has insured a stable, high pressure, high temperature turbine. On high temperature turbines, cylinder stability is a necessity for safe starting and variable load operation. To facilitate starting operation a turning gear, a jacking gear, a high pressure oiling system, and both motor and steam driven auxiliary oil pumps are used.

The generator is rated 94,117 kva at 85 per cent power factor and generates 3 phase, 60 cycle current at 22,000 volts. Its efficiency at full load unity power factor is in excess of 98.2 per cent. Actual tests showed the balanced telephone interference factor to be less than 17. The solid rotor construction, efficient rotor and stator ventilation, welded steel stator, corona-proof stator coils and external fan type cooling system have all played a part in making a real record for continuity of service.

The steam turbo-generator unit first went on the line on October 14, 1935, generating for one hour, after which it was shut down for governor adjustment. On October 17th and 18th it was operated for thirty hours, October 21st to 28th it was operated for 103 hours and on October 31st for seven hours. The three shutdowns after October 14th were made to enable adjustment of certain boiler-room equipment. During the period of November 22, 1935 to March 14, 1936, a run of 2708 hours was made before it was shut down for scheduled inspection. From October 14, 1935 to September 1, 1936, except for one general overhaul period, the unit operated 6247 hours with an average load of 50,000 kw.





REQUIREMENTS OF A CIRCUIT BREAKER

• T. G. A. Sillers
SWITCHGEAR DIVISION . . . ALLIS-CHALMERS MFG. CO.

Circuit breakers connect or isolate portions of an electrical system as dictated by the operation requirements or conditions pertinent to the system. The normal operations concerned with connecting or disconnecting apparatus from the system because of operating requirements usually mean light closing or interrupting duty, which may occur frequently or infrequently, such as once in, say, four hours or once every five minutes.

On operations caused by short circuits on a system where the defective portions or defective apparatus must be isolated, the interrupting duty is usually heavy; and, if automatic reclosing is used, the making or closing duty is also heavy. These operations are relatively rare as compared to the normal operations of merely connecting or disconnecting apparatus to meet operating needs, but cases are known where ten to fifteen such operations have occurred within an hour.

Each of these types of operations must, therefore, be considered in circuit breaker design. The mechanism must not only be capable of withstanding repeated operations for long periods of time but must likewise be capable of operating at the requisite speed after having been left in one position for a long time. These requirements necessitate low mechanical stresses and suitable materials with adequate protection to prevent damage from corrosion. The number of bearing points must be limited as much as possible, and care must be exercised in obtaining correct bearing clearances and bearing materials.

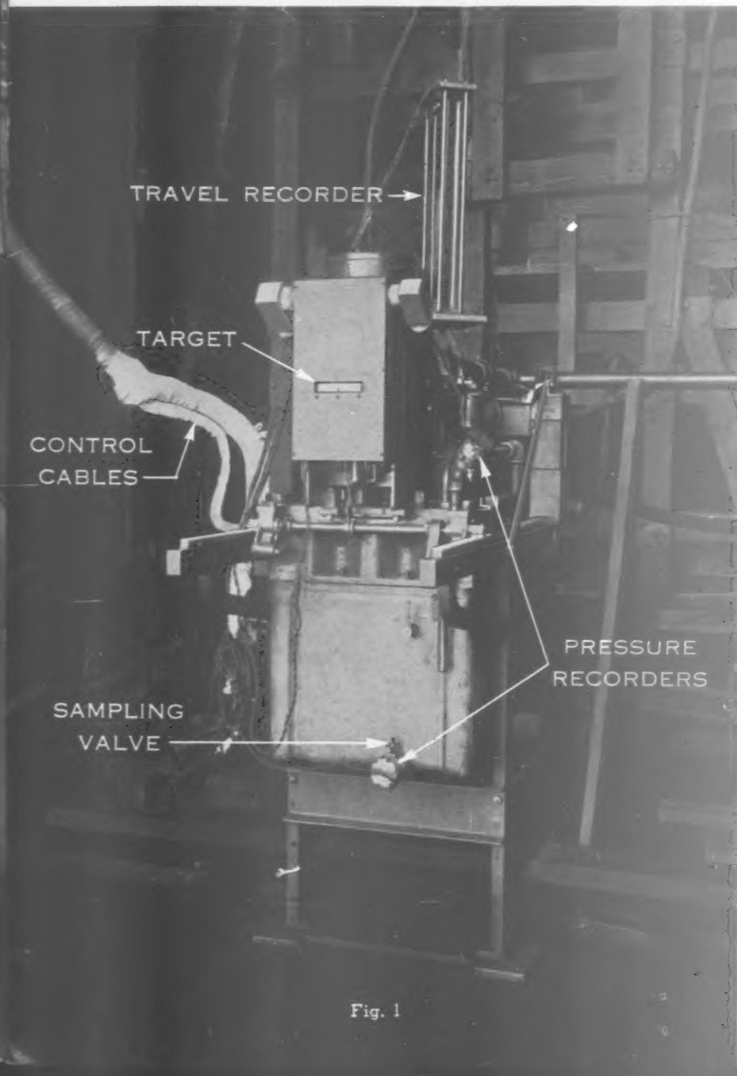


Fig. 1

Operation on short circuit is the most spectacular and probably the most discussed part of circuit breaker performance. The duty required in isolating defective portions of a system varies greatly with some ratings of breakers. For example, the 250,000 kva, 15 kv breaker illustrated in Fig. 1 may be applied on a 15 kv circuit to interrupt 10,000 amp, or it may be applied on a lower voltage circuit where the short circuit current to be interrupted may amount to a maximum of 60,000 amp.

Operating under any conditions within the range outlined, this breaker must clear a circuit involving a fault within eight cycles from the time its trip coil is energized, and it must perform this duty at least twice with a 15-second interval between operations.

Thorough testing is, of course, essential to prove the accuracy of design as well as suitability of materials. In testing the horizontal drawout, metal-clad unit shown, short circuit currents were set up in the laboratory, and the test results noted. The travel recorder and pressure recorders may be seen in the photograph.

Table I shows typical results of tests obtained with this breaker. The results of tests up to 329,500 kva, which is 131% of the breaker

rating, are indicated. The oscillogram of Figure 2 denotes typical short circuit interruption at 297,900 kva. Figure 3 shows the contacts of the breaker before testing, and Fig. 4 illustrates the condition after operation on short circuit.

During the series of tests the only visible indications of operation were the motion of the target and the jump of the power cables. There was no loss of oil either through the breaker vents or otherwise. No change of oil was made during the test. The original oil was used throughout this test without additions or without filtering. Its condition was such that at the end of the test additional operations were permissible.

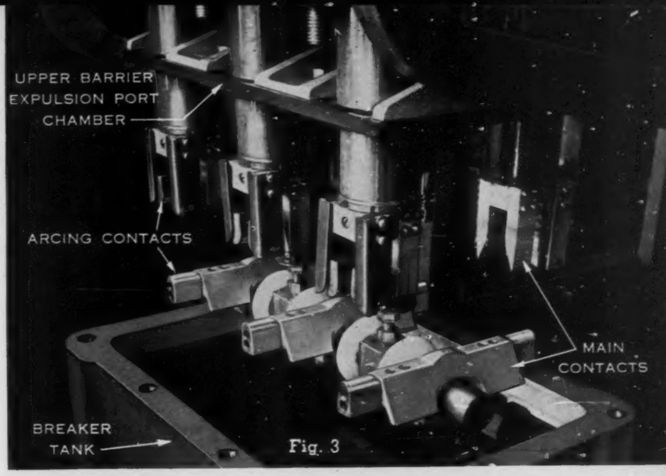


Fig. 3

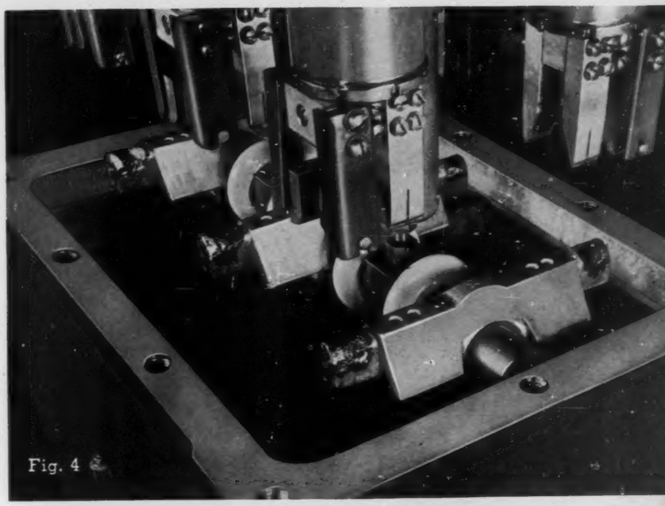


Fig. 4

TABLE I
Results of Interrupting Capacity Test on Breaker
600 Amp. 15 Kv. 250,000 Kva

Kva Interrupted	Kv	Time to Clear From Trip Impulse	Kv Oil Test	Operation
56600	12	6.8	Before 27.0	OCO-15S.
62300	12	7.0	After 27.2	OCO
146600	12	6.7	Before 27.2	OCO-15S.
137400	12	6.7	After 28.0	OCO
185700	12	6.3	Before 25.4	OCO-15S.
180100	12	6.0	After 28.4	OCO
214800	12	5.9	Before 28.4	OCO-15S.
208000	12	6.2	After 27.0	OCO
329500	12	3.8	Before 30.4	OCO-1 min.
297900	12	4.7		OCO-15S.
262900	12	5.4	After 27.8	OCO
117500	3.3	4.0	Before 22.9	OCO-15S.
111500	3.3	5.5	After 24.4	OCO
211900	3.3	3.8	Before 24.4	OCO-15S.
230300	3.3	3.9	After 19.4	OCO

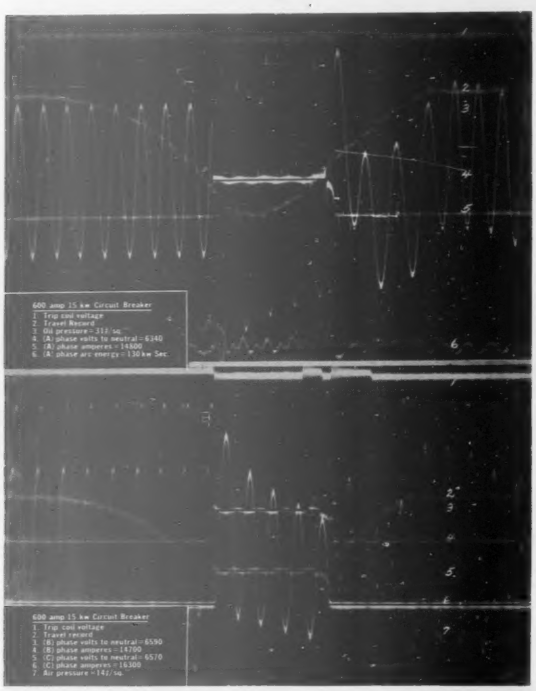


Fig. 2

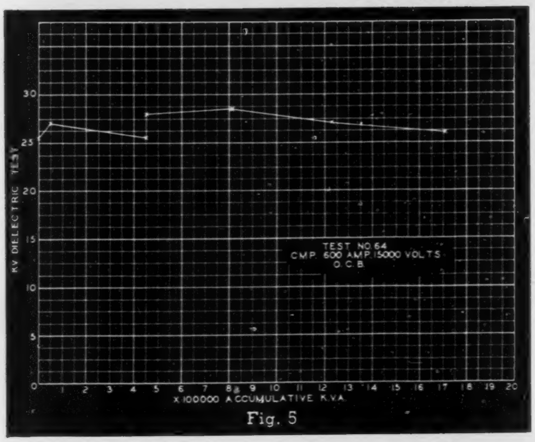
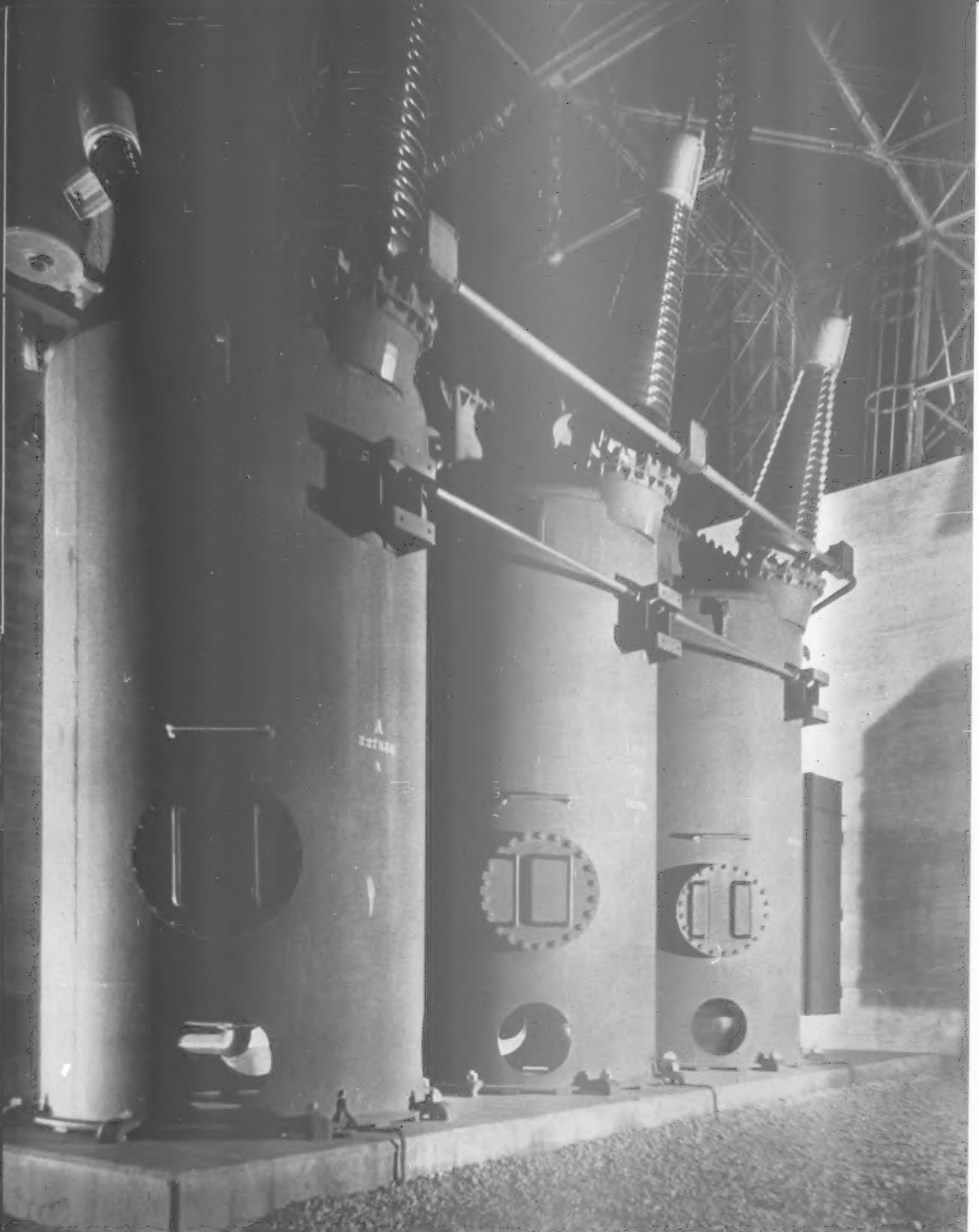


Fig. 5

Figure 5 shows the variation in dielectric strength of the oil for a cumulative kva interrupted of approximately 1,700,000.



PORT WASHINGTON CIRCUIT BREAKERS

GENERATOR EXCITATION

• L. E. Bogen
ELECTRICAL DEPT. . . . ALLIS-CHALMERS MFG. CO.

Electric generators in common use have two essential elements—a primary, or field, and a secondary, or armature. Direct current generators usually have a stationary field while alternators have a revolving field; consequently, the secondary, or armature, of an alternator is also called the stator.

This discussion of generator excitation indicates briefly the types of excitation used with modern alternators except those of the magneto type, which require special consideration.

• D-C generator excitation

A resume of the characteristics of d-c generator excitation makes clearer the service which exciters for alternators must give. There are several types of d-c generator excitation. Self-excited machines may have shunt fields or may be compound wound, either additive or subtractive; and separately excited fields may be of the simple shunt type or of the double shunt type with one winding opposing the other, called the "differential" arrangement, which may be used advantageously for some exciter windings as indicated under "Effect of Excitation." Various other combinations are possible for special purposes.

Figure 1 shows that compounding may be used to overcome not only the natural voltage droop of a shunt machine and speed droop of the prime mover, but may also provide for the drop in the line.

Figure 2 indicates an interesting possibility for small machines that is often overlooked. In this example the runaway or no-load speed of a small water wheel is 1500 rpm. The speed drops approximately uniformly with the increase in load to 650 rpm at full load. With the shunt field approximately 650/1500, or 43.5% of the total field strength, and the rest made up of the series winding, the voltage will remain sufficiently constant for the operation of lamps or even emergency excitation, without a governor on the wheel or a voltage regulator on the generator, in spite of the wide speed variation. The use of an alternator would have required both a governor and a voltage regulator.

• Effect of excitation

A saturation curve is used to show the voltage rise as generator excitation is increased. The curves of Fig. 3 show the rise in voltage under both no-load and load conditions and are based on a cold field and also on a hot field. The load consists of a constant resistance such as the field of an alternator. When the machine is self-excited, the voltage rises until the rheostat is entirely cut out and the peak voltage has risen to "ceiling" voltage. A high ceiling voltage is particularly desirable on an exciter which must respond rapidly to voltage change.

The voltage below lines OA and OB is used in the field of the machine, and the voltage between these lines and the respective curves is absorbed by the field rheostat. The vertical lines show the limit of cold and hot field excitation derived from a constant voltage source, in this case a pilot exciter, which restricts the ceiling voltage. However, the voltage available to increase the excitation is then between the lines OE and OF and the 250 volts of the pilot exciter. This allows more energy for rapidly increasing the voltage.

From Fig. 3 it may be seen that to control the voltage a rheostat must absorb more energy when a separate constant voltage source of excitation is used than when a machine is self-excited.

• Voltage response

SPEED: As indicated above, it is often necessary to know the speed at which a d-c machine can be made to change its voltage, particularly when the machine is the exciter of an alternator operating on a long line or large system.

Until recently the term "volts per second" was used to express the rapidity of the response of an exciter. That such an expression is vague can be seen from Fig. 4, which shows the no-load saturation curve of a machine in volts generated as compared to field amperes. The other curve made up for this self-excited machine indicates the rate at which the

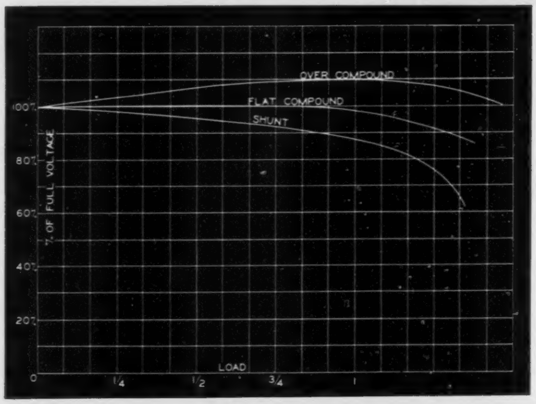


Fig. 1—D-C Generator, Self Excitation

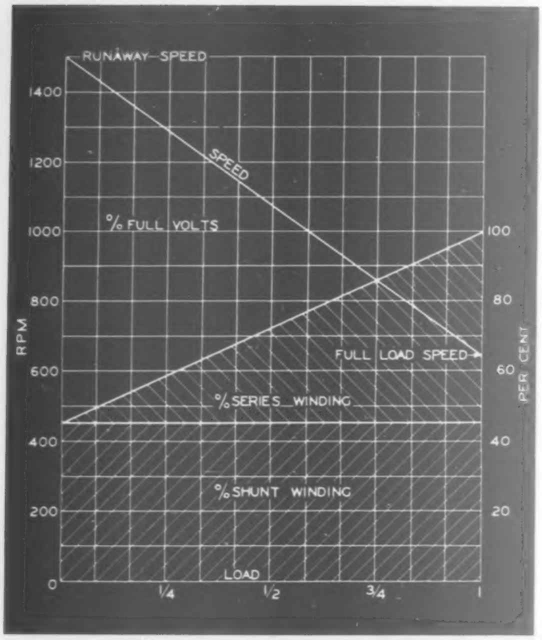


Fig. 2—Small Water-Wheel Driven D-C Generator Without Governor

voltage varies as the excitation is increased, from a rate of zero to 83 volts per second and practically back to zero.

It has become necessary, therefore, to define the

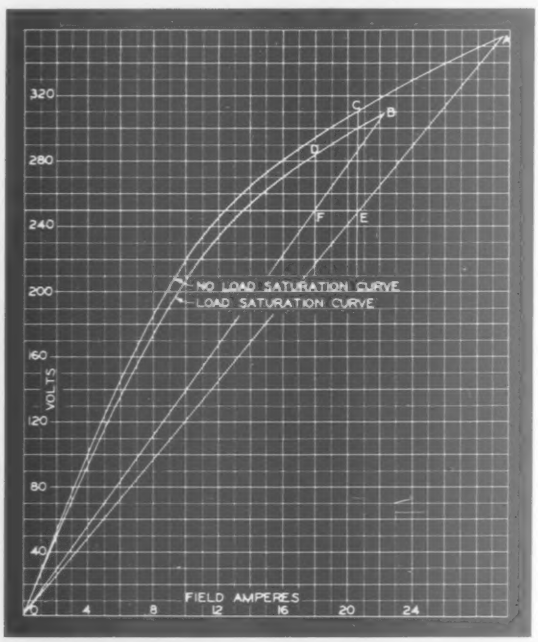


Fig. 3—Saturation Curves of 250 Volt, D-C Generator Self and Separately Excited

range over which the rate of voltage change is to be measured. As this information is chiefly concerned with exciters, the point at which the measurement or calculation starts has become generally known as "the voltage required at the slip rings at 75° C to produce the rated kva load at rated voltage power factor and frequency of the alternator" whose excitation is being considered. The average rate at which the exciter voltage changes during a half second is used as a basis, as can be seen in Fig. 5, reproduced from C-50 American Standards for Rotating Electrical Machinery, dated January 1936. It will be noted that the mean rate of voltage increase per second divided by the collector ring voltage, as mentioned above, gives the expression "nominal exciter response."

An exciter of low rpm obviously has a greater mass and therefore greater magnetic inertia than a high speed machine and considerably less "nominal response." Ordinarily a response of 0.5 is considered ample.

Figure 6 illustrates the voltage build-up curve of the same machine as that of Fig. 4, which, incidentally, is self-excited. As shown, the response in this instance is 0.78.

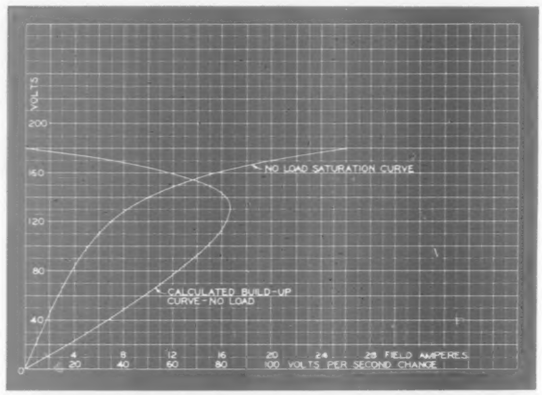


Fig. 4—Showing that Change in Volts is Not a Definite Basis

Cutting out the field rheostat resistance is, of course, necessary in order to take advantage of high response capacity of the d-c generator or exciter. One new rheostatic high speed generator voltage regulator already in extensive use has outstanding characteristics in this connection.*

It is occasionally desirable to have an exciter with nominal response above the average value of 0.5. This can be accomplished in several ways. In simple terms, the greater the force available and the easier the path through which the field excitation must flow, the more rapidly will the field build up. Hence a larger machine with a larger field winding space used

*Allis-Chalmers Electrical Review, September 1936, p. 32.

to only part of its capacity is a faster responding machine.

To improve the response of an existing machine the field coils can be arranged in two parallel paths instead of in series. This naturally calls for a larger and heavier rheostat; but by cutting it out, a big change is suddenly available to force the current through the field coils, thereby increasing the response.

A direct current machine acting as the exciter of an alternator is not likely to have more than 2 or 3% of the kilowatt capacity of the alternator, and so the small exciter has only a fraction of a second to accumulate the voltage needed to force field in-rush through the alternator rotor. As the alternator rotor is 30 to 50 times larger, it will be a matter of seconds to satisfy its need. A response of 6000 to 7000 volts per second, therefore, was not considered practical for ordinary use.

A-C generator excitation

Figure 7 indicates that the machine delivers rated capacity at 80% power factor without reaching 120 volts on the fields. This permits operating the alternator at its rated kva at 5% over-voltage, as required by A.I.E.E. rules, without raising the exciter voltage. The alternator takes 380 amp excitation with 109 volts on the fields; and with the excitation voltage maintained at 120 volts, the loss in the rheostat will be 11 x 380, or 4180 watts. If the exciter voltage is reduced, this loss can be practically eliminated. With 100% power factor instead of 80% the excitation required is only 255 amp and the rheostat would consume practically 12 kw with 120 volts at the exciter, because the voltage at the slip rings is only 73. It will be further observed that the fields require only about 50 volts at the collector rings at no load when the alternator develops 2300 volts.

The sketch shown in Fig. 8 is the usual excitation arrangement, especially with small alternators. The exciter is maintained at 120 volts, and the generator field rheostat is adjusted to give the requirement for the alternator load.

The omission of the generator rheostat requires adjustment of the exciter voltage instead. If the alternator must be operated only between F and D in Fig. 7, this should be satisfactory provided the alternator is not connected to a large system. In the case of a large system a surge through the stator may also induce a surge through the rotor; and, as this is connected to the exciter, it might demagnetize or reverse it. These surges may even destroy the collector rings.

When it is desired to operate the alternator with a low excitation for charging a line, the exciter must operate at a still lower voltage. The lower part of its saturation curve is practically a straight line; and unless the rheostat has very small steps, the voltage

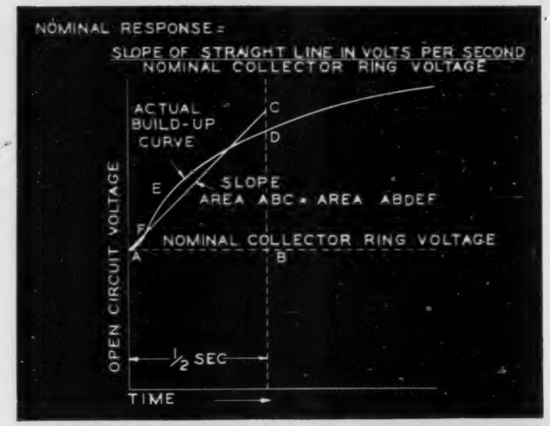


Fig. 5—Determination of Nominal Exciter Response

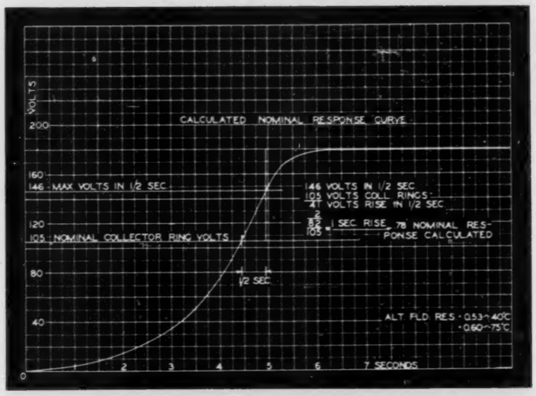


Fig. 6—Self-Excited Exciter

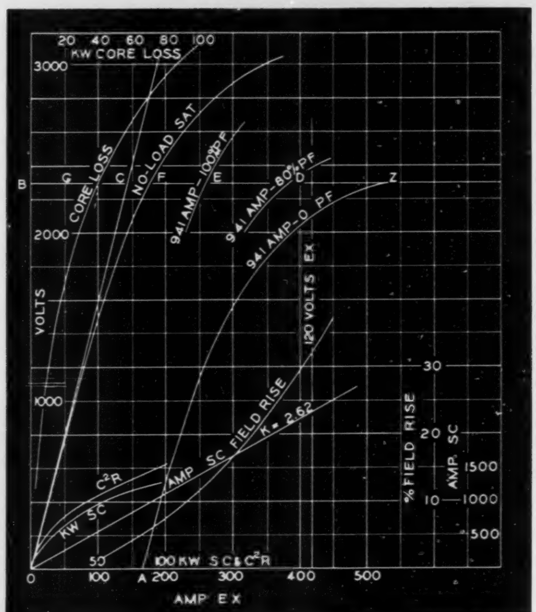


Fig. 7—Characteristic Alternator Curves. F shows the no-load saturation curve. D shows the saturation curve with 80% power factor load. Z shows the saturation curve with zero power factor load.

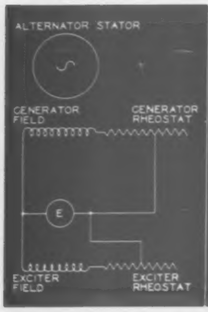


Fig. 8

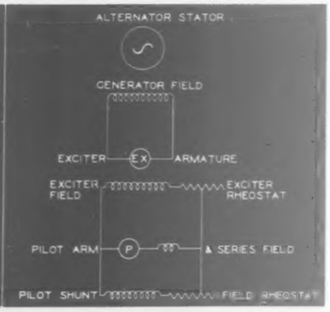


Fig. 9

will drop to the residual value. To overcome this a bend can be put in the lower part of the curve by introducing an air gap between the pole piece and the yoke, which might be called "stabilizing the exciter."

Stable operation at low voltage, however, can be cared for, particularly in larger alternators, by using a pilot exciter as shown in Fig. 9. This also has the advantage of giving more rapid voltage response, as explained previously. The voltage of the exciter can be reduced to practically residual value by having the exciter separately excited from the compound wound pilot whose voltage remains fixed.

For synchronous condensers a further step may be desirable. By putting a small winding on the exciter field opposing the main field, or in other words, differentially winding it, the exciter voltage can be reduced to zero and still be under control; that is, the field circuit will not be opened but will have a definite current in each of the two windings.

It is obvious that a differential winding can be designed to actually reverse the exciter field. This is sometimes necessary when charging a line. When it is intended to deliberately reverse the exciter voltage, however, the potentiometer method is considered more desirable. This permits complete reversal of the exciter fields.

• Stable operation

As indicated previously in this article, it is possible to have stable excitation over the entire range required by an alternator; but an alternator has its own limit of stability which is a function of its excitation.

Figure 7 shows the curves of an alternator designed for operation at 80% power factor. The ratio of BF to OA is a measure of the holding-together power of the field and armature of a machine designed for satisfactory operation at 80% power factor. Suppose, however, that the line conditions were such that it operated at G and an effort were made to have it deliver the same number of kilowatts, not kva, it is evident that the magnetic tie between field and armature would probably be too weak.

The remedy is again a matter of excitation. Changing the power factor of the load, possibly changing the voltage a little, varying the number of turns in the stator winding slightly, will all help. If, however, point G could be moved over to E, point F would move over close to D, and the new resultant BF would be so much larger than it was that operation would again be satisfactory. This can be accomplished simply by enlargement of the air gap, which is practicable, but the machine does not retain its ability to operate at 80% power factor without overheating its fields. Electrically speaking the short circuit ratio has been increased.

• Mechanical arrangement of exciters

Exciters direct connected to the alternator so as to be driven by the same prime mover are usually desirable. For slow speed alternators, however, they are expensive and also sluggish. This is overcome on horizontal machines by belting the exciter. On vertical machines a motor generator exciter set is frequently used. The use of a motor generator set is considered impractical by some, because when the alternator breaker is tripped, the motor generator stops and removes excitation from the alternator. The fact that the station can be easily started up again is often overlooked. Reference to Fig. 7 shows that to develop half voltage on the alternator requires only about 25 volts and 80 amp or about 4% of the capacity of the exciter. A few automobile batteries would do this easily on this 3750 kva alternator.

Figure 10 is an oscillogram taken to determine the actual nominal exciter response and is self-explanatory.

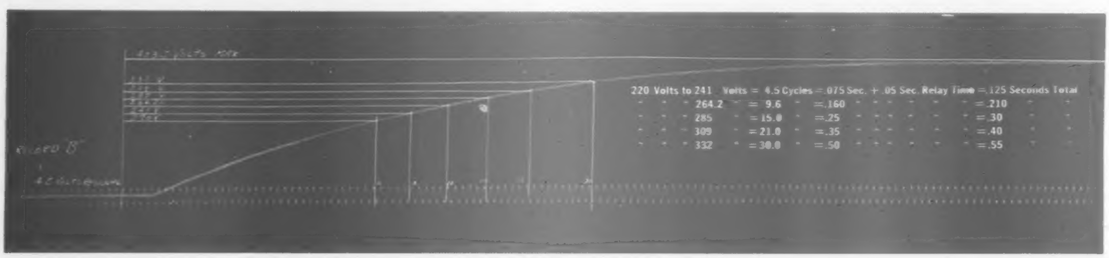


Fig. 10

THREE- AND FOUR-WINDING TRANSFORMERS*

• W. C. Sealey
TRANSFORMER DIVISION . . . ALLIS-CHALMERS MFG. CO.

In applying the theory of the multiple winding transformer to specific problems, the general method to be followed is the same as for the solution of any electrical circuit. One additional step is required, namely, the derivation of the equivalent circuit with its numerical values from the actual circuit. The starting point in every instance is the actual circuit of the transformer with its numerical values. From the actual circuit the equivalent circuit is derived as described in a preceding article.

Using this equivalent circuit, equations may be set up involving the known and unknown quantities of the circuit. These equations are solved simultaneously if it is necessary to write more than one equation. The general principles used to set up the relation between the currents and voltages of the circuit are the fundamental principles of electrical circuits, such as Ohm's law. This is the fundamental algebraic method.

A modification of this general method which consists of solving the problem step by step, using one equation at a time and determining unknown quantities successively, is often convenient particularly when more than one unknown quantity is to be evaluated. When analyzed, this method is seen to consist of setting up an equation to determine one unknown; then setting up another equation to determine another unknown, and so on successively until all the required unknown quantities have been evaluated.

When the unknown quantities have been determined for the equivalent circuit, these values can be readily converted into values for the actual circuit.

The application of these principles to various types of fundamental problems will be outlined in considerable detail. The solution of more complicated problems generally consists of applying these same fundamental principles in a similar way. An understanding of the simple applications is the principal requirement for the solution of the more complex problems.

In obtaining a numerical solution the use of complex quantities results in appreciable simplification when it is necessary to take both the resistance and reactance of the circuit into account. The examples shown are confined to single-phase transformers since the same principles apply to three-phase circuits. A balanced three-phase circuit may be divided into three single-phase circuits each of which has the same numerical solution. Where it is necessary to solve a three-phase circuit with equations involving all three phases, the same method is used and the same general principles apply as for single-phase circuits.

• Example A

Determination of current and voltage relations for a three-winding transformer under various load conditions.

A single-phase, three-winding transformer has the following characteristics:

HV 10000 kva 66000 volts (151.5 amp at full load)
LV 10000 kva 13200 volts (757.6 amp at full load)
TV 5000 kva 2200 volts (2273 amp at full load)

Based on 10000 kva, reactance from HV to LV=10%; cu loss=80 kw.

Based on 5000 kva, reactance from HV to TV=10%; cu loss=50 kw.

Based on 5000 kva, reactance from LV to TV= 8%; cu loss=60 kw.

Required:

1. Determine the equivalent circuit.
2. If power is supplied from the HV lines and the load on the LV winding is 500 amperes at 86.6% power factor lagging and the load on the TV winding is 600 amperes at 90% power factor leading with respect to the primary voltage, what is the load on the primary?
3. If the voltage applied to the HV is 66000 volts, what is the voltage of the HV and TV windings when they are loaded as in (2)?
4. If 66000 volts is applied to the HV, what will be the voltage at the TV terminals when the LV is short circuited?
5. If 66000 volts is applied to the HV, what current will flow on a combined short circuit of the LV and TV windings, and how will it divide between them?

*Continued from Allis-Chalmers Electrical Review, Sept., 1936.

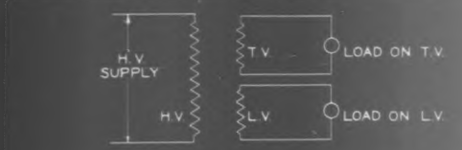


Fig. 10 a

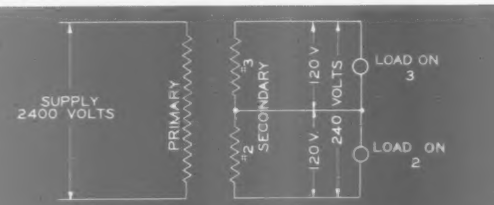


Fig. 11 a

NOTE: VOLTAGES SHOWN ARE RATED VOLTAGE OF THE WINDINGS

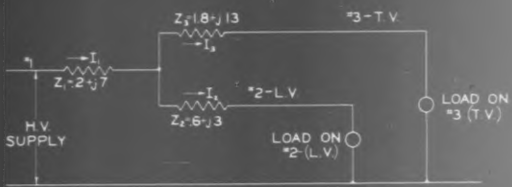


Fig. 10 b

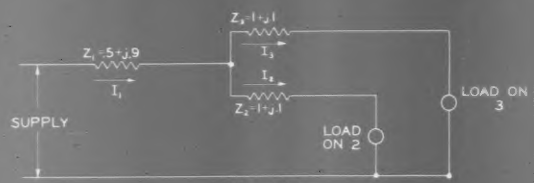


Fig. 11 b

SOLUTION OF 1 To determine the equivalent circuit. (The actual circuit is shown in Fig. 10a.)

To determine the impedance values in the equivalent circuit, the general method is to write expressions for the per cent impedance between the various windings with the third winding idle. These impedance values when reduced to the same kva basis are substituted in the general formulae of Part II to determine the numerical value of the impedances of the equivalent circuit.

The per cent impedance at a given kva =

$$\frac{\text{cu loss in kw at given kva x 100}}{\text{given kva}} + j \text{ (per cent reactance at given kva)}$$

$$\text{Per cent impedance HV to LV} = \frac{80 \times 100}{10000} + j10 = .8 + j10 \text{ at 10000 kva.}$$

$$\text{Per cent impedance HV to TV} = \frac{50 \times 100}{5000} + j10 = 1 + j10 \text{ at 5000 kva.}$$

$$\text{Per cent impedance LV to TV} = \frac{60 \times 100}{5000} + j8 = 1.2 + j8 \text{ at 5000 kva.}$$

To determine the equivalent circuit all impedances must be expressed on the same kva basis. Consequently at 10000 kva (since the per cent impedance varies directly with the kva):

$$\text{Impedance HV to LV} = .8 + j10$$

$$\text{Impedance HV to TV} = \frac{10000}{5000}(1 + j10) = 2 + j20$$

$$\text{Impedance LV to TV} = \frac{10000}{5000}(1.2 + j8) = 2.4 + j16$$

If the HV winding is designated as No. 1, the LV winding as No. 2, and the TV winding as No. 3, then:

$Z_{12} = .8 + j10$

$Z_{13} = 2 + j20$

$Z_{23} = 2.4 + j16$

Substituting in the equations of Part II

$$Z_1 = \frac{Z_{12} + Z_{13} - Z_{23}}{2} = \frac{.8 + j10 + 2 + j20 - (2.4 + j16)}{2} = .2 + j7$$

$$Z_2 = \frac{Z_{12} + Z_{23} - Z_{13}}{2} = \frac{.8 + j10 + 2.4 + j16 - (2 + j20)}{2} = .6 + j3$$

$$Z_3 = \frac{Z_{13} + Z_{23} - Z_{12}}{2} = \frac{2 + j20 + 2.4 + j16 - (.8 + j10)}{2} = 1.8 + j13$$

The equivalent circuit for this transformer is shown in Fig. 10b.

SOLUTION OF 2 If power is supplied from the HV line and the load on the LV winding is 500 amperes at 86.6% power factor lagging with respect to the primary voltage and the load on the TV winding is 600 amperes at 90% power factor leading with respect to the primary voltage, what is the load on the primary?

The general method of solution for the current in one winding of a three winding transformer, when the currents in the other two windings are given, is to indicate positive directions of current in the several windings as shown by the arrows in Fig. 10b and then write the equation covering the relation of the currents. In this case, the relation is, by inspection of Fig. 10b, $I_1 = I_2 + I_3$ (when all currents are expressed as vector quantities). A simple method of reducing all currents for a 1 to 1 ratio of transformation is to express the currents in per cent of a given nominal kva. (The nominal kva is the product of the no load kv of a winding and the current in it).

$$\text{That is, the per cent load on a winding} = \frac{\text{100 x nominal kva load}}{\text{given nominal kva}}$$

In this case the nominal kva load on 2 =

$$500\,(.866 - j5) \times 13.2 = 5716 - j3300$$

The nominal kva on 3 = 600 (.9 + j.436) 2.2 = 1188 + j576

$$I_2 = \text{The per cent load on } 2 = \frac{100 \times (5716 - j3300)}{10000} = 57.16 - j33$$

I_3 = The per cent load on $3 = \frac{100 x (1188+j576)}{10000} = 11.88+j5.76$

$I_1 = I_2 + I_3 = 57.16 - j33 + 11.88 + j5.76 = 69.04 - j27.24$

The nominal kva on winding $1 = \frac{10000}{100} x (69.04 - j27.24) = 6904 - j2724$

The power factor of the load on $1 = \frac{6904 x 100}{\sqrt{(6904)^2 + (2724)^2}} =$ 93 per cent lagging.

The numerical value of the nominal kva on winding 1 =

$\sqrt{\overline{6904}^2 + \overline{2724}^2} = 7420$ kva

The numerical value of the nominal kva on winding 2 = 500 x 13.2 = 6600 kva

The numerical value of the nominal kva on winding 3 = 600 x 2.2 = 1320 kva

SOLUTION OF 3 If the voltage applied to the HV is 66000 volts, what is the voltage of the LV and TV windings when they are loaded as in (2)?

Referring to Fig. 10b, the voltage at the terminals of the LV winding is equal to the applied voltage minus the voltage drop through the impedance in the circuit to the terminals of the LV windings. A similar relation holds for the TV winding. If the impedance drop with load conditions as described is calculated and subtracted vectorally from the applied voltage, the remainder is the terminal voltage.

As previously determined, the current I_1 in per cent of full load (10000 kva) = 69.04—j27.24.

The per cent voltage drop through $Z_1 = I_1 Z_1 = \frac{(69.04 - j27.24)}{100} (.2+j7) = 2.04+j4.78$

Similarly the per cent voltage drop through $Z_2 = I_2 Z_2 = \frac{(57.16 - j33)}{100} (.6+j3) = 1.33+j1.52$

and through $Z_3 = I_3 Z_3 = (11.88+j5.76)(1.8+j13) = -.54+j1.65$

The voltage drop from 1 to $2 = I_1 Z_1 + I_2 Z_2 = 2.04+j4.78+1.33+j1.52 = 3.37+j6.30$

and the voltage drop from 1 to $3 = I_1 Z_1 + I_3 Z_3 = 2.04+j4.78 - .54 + j1.65 = 1.50+j6.43$

The voltage applied to winding 1 = 100 per cent; the per cent voltage on winding 2 = 100—voltage drop from 1 to 2 = 100—(3.37 +j6.30) = 96.63—j6.3.

The scalar value equals $\sqrt{\overline{96.63}^2 + \overline{6.3}^2} = 96.8$ per cent.

The voltage at the terminals of winding $2 = \frac{96.8}{100} x 13200 =$ 12800 volts

The per cent voltage on winding 3 = 100—voltage drop from 1 to 3 = 100—(1.5+j6.43) = 98.5—j6.43.

The scalar value equals $\sqrt{\overline{98.5}^2 + \overline{6.43}^2} = 98.6$ per cent.

The voltage at the terminals of winding $3 = \frac{98.6}{100} x 2200 = 2170$ volts.

SOLUTION OF 4 If 66000 volts is applied to the HV, what will be the voltage at the TV terminals when the LV is short circuited?

To obtain the voltage on the TV winding when the LV winding is short circuited, the first step is to calculate the short circuit current which will flow. With the short circuit current determined, the voltage drop through the circuit to the TV winding can be determined. If the voltage drop to the TV terminals is subtracted vectorally from the applied voltage, the remainder is the voltage at the TV terminals.

Under these conditions the impedance of the load itself on the LV (winding 2) is zero. (See Fig. 10b). The load impedance of the load itself on the TV (winding 3) is infinite.

The impedance to the short circuit current $= Z_1 + Z_2 = .2+j7+.6+j3 = .8+j10$

The current in the short circuit in terms of F. L. current at 10000 kva $= \frac{E}{I} = \frac{100}{.8+j10} = \frac{100}{.8+j10} x \frac{.8-j10}{.8-j10} = \frac{80-j1000}{.64+100} = .79-j9.93$

The voltage drop through the primary impedance = (.79—j9.93) (.2+j7) = 69.7+j3.6

The load on winding 3 is zero. The impedance drop through Z_3 is therefore zero. The voltage on the TV (winding 3) = 100—(69.7+j3.6) = 30.3—j3.6.

The scalar value of the per cent voltage $= \sqrt{\overline{30.3}^2 + \overline{3.6}^2} = 30.5$ per cent

The voltage at the terminals of the TV winding =

$\frac{30.5}{100} x 2200 = 671$ volts

SOLUTION OF 5 If 66000 volts is applied to the HV, what current will flow on a combined short circuit of the LV and TV windings and how will it divide between them?

To determine the current when combined short circuits exist, the impedance under combined short circuits is calculated. From this impedance value the total current is calculated. The total current divides between the short circuited windings inversely proportional to their impedances.

Referring again to Fig. 10b the impedance on the combined short circuit on windings 2 and 3 with power supplied from winding 1 =

$$.2+j7+\frac{1}{\frac{1}{.6+j3}+\frac{1}{1.8+j13}} = .2+j7+.46+j2.44 = .66+j9.44$$

The current in the HV (winding 1) in terms of full load current at 10000 kva $= \frac{100}{.66+j9.44} = .74-j10.6$

The current in the HV $= \left(\sqrt{\overline{.74}^2 + \overline{10.6}^2}\right) x 151.5 = 10.6 x 151.5 =$ 1610 amps.

Referring to Fig. 10b this current will divide between the LV winding and the TV winding inversely proportionally to their impedances.

The current in the LV in terms of full load current at 10,000 kva $= 10.6 x \frac{1.8+j13}{1.8+j13+.6+j3} = 10.6 (.81+j.009) = 8.6+j.095$

The current in the LV winding $= \left(\sqrt{\overline{8.6}^2 + \overline{.095}^2}\right) x 757.6 = 6500$ amp. The current in the TV in terms of the full load current at 10,000 kva =

$10.6 x \frac{.6+j3}{1.8+j13+.6+j3} = 10.6 (.19 - j.009) = 2.0 - j.095$

The current in the TV winding $= \left(\sqrt{\overline{2.0}^2 + \overline{.095}^2}\right) x 2273 x 2 =$ 9600 amp.

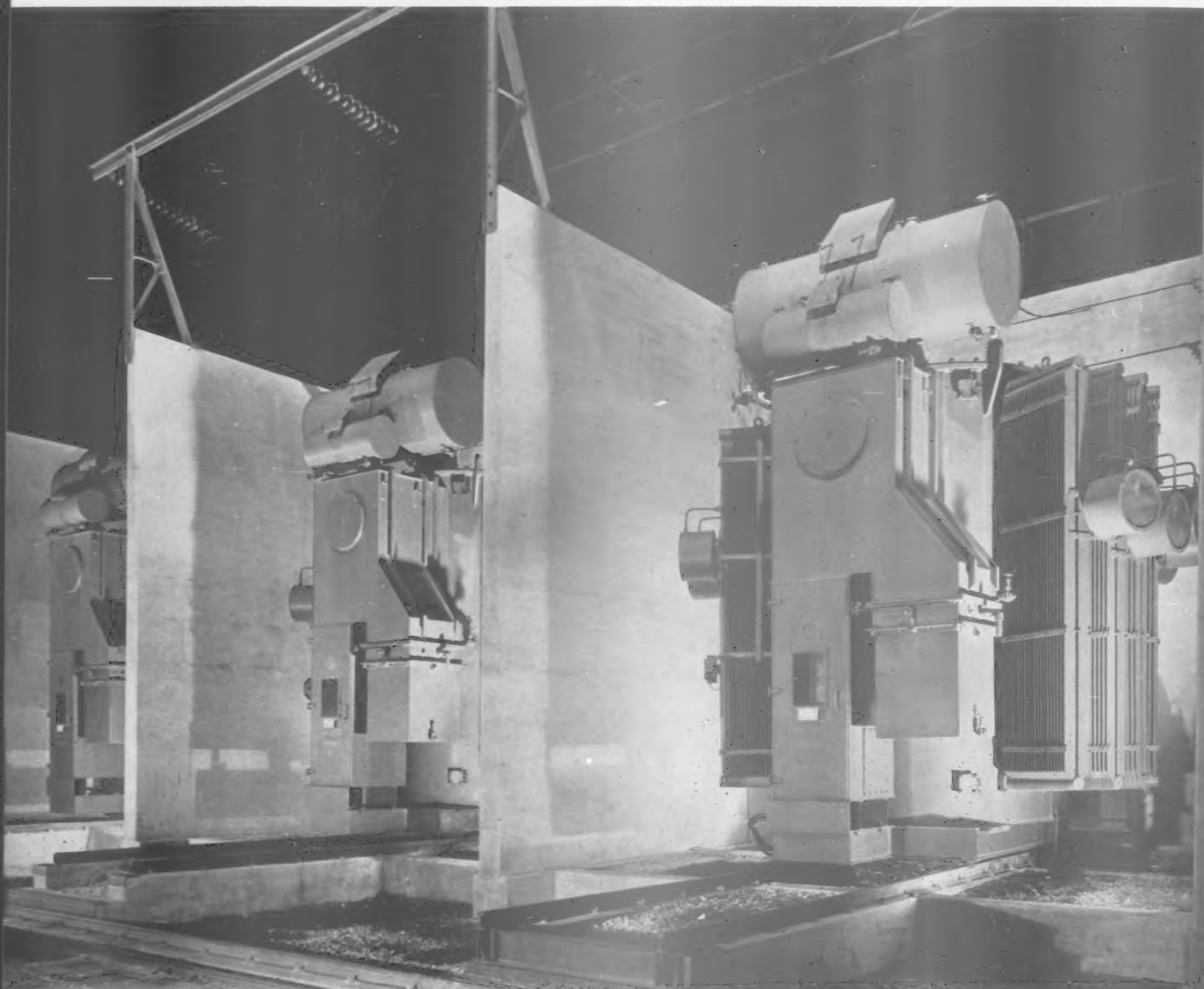
• Example B

The theory of the multiple winding transformer may be used to solve for current and voltage relations when winding connections are more complicated than with the ordinary two-winding transformer. A standard distribution transformer with 2400 volts primary and 120/240 three wire secondary is an example of such a case. Due to the mutual inductance between the windings, a load on one 120 volt circuit affects the voltage on the other 120 volt circuit. The circuit diagram is shown in Fig. 11a. The equivalent circuit using the theory of multiple winding transformers is shown in Fig. 11b. When the constants of the equivalent circuit have been determined, the circuit may be used for a multiplicity of problems involving load division and voltage regulation.

For example the transformer in Fig. 11 may have the following characteristics:

10 kva single-phase 60 cycles
HV 2400
LV 120/240—3 wire.

PORT WASHINGTON TRANSFORMERS



Reactance Volts HV to LV No. 2 based on full load current in primary 2 per cent—Copper loss 300 watts.

Reactance Volts HV to LV No. 3 based on full load current in primary 2 per cent—Copper loss 300 watts.

Reactance Volts LV No. 2 to LV No. 3 based on full load current in secondary .2 per cent—Copper loss 100 watts.

For each half of the total secondary winding, the kva at full load current equals half the transformer rating, or 5 kva. If the impedances are expressed in per cent based on 5 kva, then:

$$Z_{12} = \frac{300 \times 100}{10000} \times \tfrac{1}{2} + j\tfrac{1}{2} \times 2 = 1.5 + j1$$

$$Z_{13} = \frac{300 \times 100}{10000} \times \tfrac{1}{2} + j\tfrac{1}{2} \times 2 = 1.5 + j1$$

$$Z_{23} = \frac{100 \times 100}{5000} + j.2 = 2 + j.2$$

Using the equations of Part II:

$$Z_1 = \frac{Z_{12} + Z_{13} - Z_{23}}{2} = \frac{1.5 + j1 + 1.5 + j1 - (2 + j.2)}{2} = .5 + j.9$$

$$Z_2 = \frac{Z_{12} + Z_{23} - Z_{13}}{2} = \frac{1.5 + j1 + 2 + j.2 - (1.5 + j1)}{2} = 1 + j.1$$

$$Z_3 = \frac{Z_{13} + Z_{23} - Z_{12}}{2} = \frac{1.5 + j1 + 2 + j.2 - (1.5 + j1)}{2} = 1 + j.1$$

In using this equivalent circuit for a 240 volt load, the total load may be represented by two loads, each of one-half the kva of the 240 volt load—one load on winding No. 2 and one on winding No. 3.

PROBLEM:

If this transformer carries 10 kva at 80 per cent power factor lagging with 120 volts on winding No. 2, and no load on winding No. 3, what will be the voltage at the terminals of winding No. 3? What is the applied voltage on the primary?

Referring to Fig. 11b, the voltage drop through Z_3 is zero since winding No. 3 carries no current. The voltage at the terminals of winding No. 3 = E_3.

$\%E_3 = 100 +$ (per cent voltage drop through Z_2) $= 100 + 2\,(.8 - j.6)\,(1 + j1) = 101.72 - j1.04$.

$$E_3 \text{ in volts} = 120\sqrt{\overline{101.72}^2 + \overline{1.04}^2} = 122 \text{ volts}$$

The voltage applied to the primary = E_1

$$\%E_1 = 100 + 2\,(.8 - j.6)\,(1.5 + j1) = 103.6 - j.2$$

$$E_1 \text{ in volts} = 2400\sqrt{\overline{103.6}^2 + \overline{.2}^2} = 2490 \text{ volts}$$

Note that at no load on all windings the voltage on winding 3 would be 124.5 volts. The load on winding 2 reduces the voltage of winding 3 from 124.5 volts to 122 volts. It also reduces the voltage of winding 2 from 124.5 to 120 volts.

Using this equivalent circuit, performance curves can be calculated using different conditions of loading. Sometimes it is more convenient to express the current in amperes and the impedance in ohms, as, for example, when the impedance of a secondary line is considered in the solution. This does not change the method of solution, but merely the numerical values.

• Example C

The use of the equivalent circuit for the four-winding transformer. The circuit for the four-winding transformer may be used in similar fashion as the circuit for the three-winding transformer. The application is really no more difficult, but the work involved is considerably greater because of the greater number of impedance links in the equivalent circuit. In the examples given for the four-winding transformer, the applications will be shown in complete detail to save the reader time in following the solution in determining the details of the application.

A four-winding transformer has the following characteristics:

Winding	Kva	Voltage
No. 1	10000	132000
No. 2	10000	66000
No. 3	5000	13200
No. 4	5000	6600

Winding	Reactance Percent	Copper Loss kw	Kva Base for Reactance and Copper Loss
1 to 2	10	50	10000
1 to 2	6	20	5000
1 to 4	8	20	5000
2 to 3	4	25	5000
2 to 4	7	25	5000
3 to 4	4	30	5000

The circuit diagram of this transformer is shown in 12a.

1. Determine the equivalent circuit.
2. If power is supplied from the HV lines and the load on the winding 2 is 4000 kva (nominal) at 80% power factor lagging with respect to the primary voltage, and the load on winding 3 is 3000 kva (nominal) at 60% power factor leading with respect to the primary voltage, what is the load on the primary?
3. If the voltage applied to the HV is 132,000 volts, what is the voltage of the other windings when loading conditions are as given in part 2?
4. If 132,000 volts is applied to the HV, what will be the voltage of the other windings when winding 2 is short circuited?

SOLUTION OF 1 To determine the equivalent circuit.

Winding	Impedance based on 10000 kva		Impedance
1 to 2	$\frac{50 \times 100}{10000} + j10 = .5 + j10$	=	Z_{12}
1 to 3	$\left(\frac{20 \times 100}{5000} + j6\right)2 = .8 + j12$	=	Z_{13}
1 to 4	$\left(\frac{20 \times 100}{5000} + j8\right)2 = .8 + j16$	=	Z_{14}
2 to 3	$\left(\frac{25 \times 100}{5000} + j4\right)2 = 1.0 + j8$	=	Z_{23}
2 to 4	$\left(\frac{25 \times 100}{5000} + j7\right)2 = 1.0 + j14$	=	Z_{24}
3 to 4	$\left(\frac{30 \times 100}{5000} + j4\right)2 = 1.2 + j8$	=	Z_{34}

Substituting in the equations of Part II (in each case the equations used are those developed in Part II)

$$A = Z_{13} + Z_{24} - Z_{12} - Z_{34} = .8 + j12 + 1.0 + j14 - (.5 + j10) - (1.2 + j8) = .1 + j8$$

$$B = Z_{13} + Z_{24} - Z_{14} - Z_{23} = .8 + j12 + 1.0 + j14 - (.8 + j16) - (1.0 + j8) = 0 + j2$$

$$\sqrt{AB} = \sqrt{(.1 + j8)\, j2} = \sqrt{-16 + j.2} =$$

$$\sqrt[4]{\overline{16}^2 + \overline{.2}^2}\ \sqrt{e^{j\tan^{-1}\left(\frac{.2}{-16}\right)}} = \sqrt[4]{\ }\sqrt{e^{j(179^\circ\ 17')}} =$$

$$4e^{j(89^\circ 39')} = 4(\cos 89^\circ\ 39' + j\sin 89^\circ\ 39') = 4(.0062 + j1.0) = .025 + j4$$

$$Z_5 = A + \sqrt{AB} = .1 + j8 + .025 + j4 = .125 + j12$$

$$Z_6 = B + \sqrt{AB} = 0 + j2 + .025 + j4 = .025 + j6$$

$$Z_1 = \tfrac{1}{2}(Z_{13} + Z_{12} - Z_{23} - Z_6) = \tfrac{1}{2}[.8 + j12 + .5 + j10 - (1 + j8) - (.025 + j6)] = .14 + j4$$

$$Z_2 = \tfrac{1}{2}(Z_{24} + Z_{23} - Z_{34} - Z_5) = \tfrac{1}{2}[1 + j14 + 1 + j8 - (1.2 + j8) - (.125 + j12)] = .34 + j1$$

$$Z_3 = \tfrac{1}{2}(Z_{13} - Z_{12} + Z_{23} - Z_5) = \tfrac{1}{2}[.8 + j12 - (.5 + j10) + 1 + j8 - (.125 + j12)] = .59 - j1$$

$$Z_4 = \tfrac{1}{2}(Z_{24} - Z_{23} + Z_{34} - Z_6) = \tfrac{1}{2}[1 + j14 - (1 + j8) + 1.2 + j8 - (.025 + j6)] = .59 + j4$$

These values are shown on the equivalent circuit (Fig. 12b). The arrows shown indicate the positive direction of current flow which is assumed.

SOLUTION OF 2 If power is supplied from the HV lines and the load on winding 2 is 4000 kva (nominal) at 80% power factor lagging with respect to the primary voltage and the load on the winding 3 is 3000 kva (nominal) at 60% power factor leading with respect to the primary voltage, what is the load on the primary?

The kva load on the LV = 4000 (.8+j.6) = 3200—j2400
The kva load on the TV = 3000 (.6+j.8) = 1800+j2400
Adding, the kva load on the HV = 5000+j0
The load on the HV is 5000 kva at 100% power factor.

SOLUTION OF 3 If the voltage applied to the HV is 132,000 volts, what is the voltage of the other windings when loading conditions are as given in part 2.

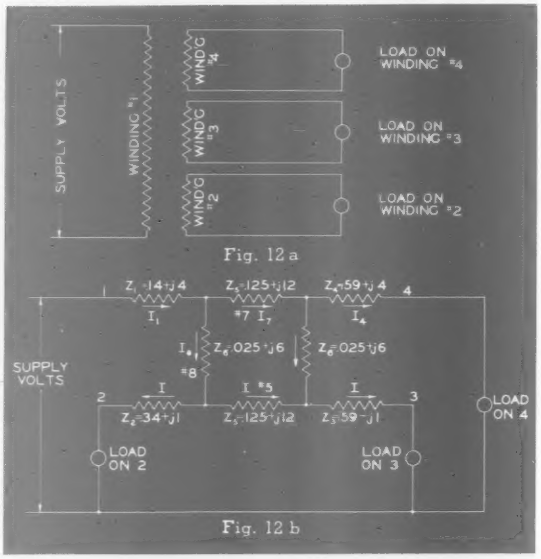


Fig. 12 a

Fig. 12 b

The first step in this problem is to determine the per cent currents flowing in the various links of the circuit of Fig. 12b. When these currents have been determined, the per cent voltage drops are calculated. When these per cent voltage drops are subtracted from the applied per cent voltage, the remainder is the voltage at the terminals to which the voltage drop is calculated.

In determining the division of load currents, the principle of superposition is convenient. The current division is calculated for each load as if the other loads did not exist. The total current in the links of the circuit is determined by superimposing the individual currents thus obtained. If a calculating board is available, it is evident that if the equivalent circuit (Fig. 12b) is set up and voltage impressed on the circuit, the values of impedance drop and current division can be read directly.

The per cent load on winding $2 = (3200 - j2400) \times \frac{100}{10000} = 32 - j24 = I_2$

The per cent load on winding $3 = (1800 + j2400) \times \frac{100}{10000} = 18 + j24 = I_3$

The per cent load on winding $1 = I_2 + I_3 = 32 - j24 + 18 + j24 = 50 + j0 = I_1$

The load current of winding 2 will divide between link 8 and links 5, 6, and 7 in series, inversely proportionally to their impedances.

Let the current in branch 8, due to load on winding 2 $= I_{8L}$

Then $I_{8L} = \frac{2Z_5+Z_6}{2\,(Z_5+Z_6)} \times (32-j24) = \frac{2\,(.125+j12)+.025+j6}{2\,(.125+j12+.025+j6)} \times$

$(32-j24) = \frac{(.275+j30)\ (32-j24)}{.30+j36} = \frac{(.275+j30)\ (32-j24)}{.30+j36} \times$

$\frac{.30-j36}{.30-j36} = \frac{34500-j25900}{.30^2+36^2} = 26.1-j20$

$-I_5 = I_6 = I_7 = 32-j24-I_{8L} = 32-j24-(26.6-j20) = 5.4-j4$

The load current of winding 3 will divide equally between links 5 and 8 and links 6 and 7 since these two circuits, which are in parallel, have equal impedances. One-half of the load on winding 3 will flow in each branch.

The current in each branch due to the load on 3 $= \frac{1}{2}\,(18+j24) = 9+j12$.

The total current in branch 5 $= 9+j12-(5.4-j4) = 3.6+j16 = I_5$
The total current in branch 6 $= 9+j12+5.4-j4 = 14.4+j8 = I_6$
The total current in branch 7 $= 9+j12+j.4-j4 = 14.4+j8 = I_7$
The total current in branch 8 $= 9+j12+26.6-j20 = 35.6-j8 = I_8$

The per cent voltage at the terminals of winding 2 = the per cent voltage applied to winding 1 minus the voltage drop through the circuit to the terminals of winding 2 $= 100-\frac{1}{100}\,(I_1Z_1+I_8Z_6+I_2Z_2) = 100-\frac{1}{100}50\,(.14+j4)+(35.6-j8)\ (.025+j6)+(32-j24)\ (.34+j1) = 100-(.91+j4.37) = 99.09-j4.37$

The voltage at the terminals of winding 2 $= \left(\sqrt{\overline{.9909}^2+\overline{.0437}^2}\right) \times 66000 = 65500$ volts.

The per cent voltage at the terminals of winding 3 equals the per cent voltage applied to winding 1 minus the voltage drop through the circuit to the terminals of winding 3 $= 100-\frac{1}{100}\,(I_1Z_1+I_8Z_6+I_5Z_5+I_3Z_3) = 100-\frac{1}{100}\Big[50\ \ (.14+j4)+(35.6-j8)\ \ (.025+j6)$ $+(3.6+j16)\ \ (.125+j12)+(18+j24)\ \ (.59-j1)\Big] = 100-$ $(-1.02+j4.54) = 101.02-j4.54$:

The voltage at the terminals of winding 3 =
$\frac{1}{100}\left(\sqrt{\overline{101.02}^2+\overline{4.54}^2}\right) \times (13200) = 13330$ volts.

The per cent voltage at the terminals of winding 4 = the per cent voltage applied to winding 1 minus the voltage drop through the circuit to the terminals of winding 4 $= 100-\frac{1}{100}\,(I_1Z_1+I_7Z_5) =$ $100-\frac{1}{100}\Big[50\ (.14+j4)+(14.4+j8)\ (.125+j12)\Big] = 100-$ $(-.87+j3.74) = 100.87-j3.74$

The voltage at the terminals of winding 4 =
$\frac{1}{100}\left(\sqrt{\overline{100.87}^2+\overline{3.74}^2}\right) \times 6600 = 6660$ volts.

SOLUTION OF 4 If 13200 volts is applied to the HV, what will be the voltage of winding 4 when winding 2 is short circuited?

Under these conditions the load on winding 2 has an impedance of zero (See Fig. 12b). The other loads have an impedance of infinity.

The impedance to the short circuit $= Z_{12} = .5+j10$. The total per cent current in winding 1 on short circuit $= \frac{100}{.5+j10} \times 100 =$

$\frac{10000}{.5+j10} \times \frac{.5-j10}{.5-j10} = \frac{5000-j100000}{.25+100} = 49.9-j998 = I_1$

The per cent of full load current in the HV $= \sqrt{\overline{49.9}^2+\overline{998}^2} =$ 999 per cent of full load current. The total full load current divides between the links of the circuits inversely proportionally to the impedances.

The per cent current $I_7 = \frac{Z_6}{2\,(Z_5+Z_6)} \times (49.9+j998) = \frac{(.025+j6)}{2(.15+j18)}$ $\times (49.9-j998) = \frac{(.025+j6)}{.3+j36} \times (49.9-j998) \times \frac{.3-j36}{.3-j36} = 9-j167.$

The per cent voltage at the terminals of winding 4 = the per cent voltage applied to winding 1 minus the voltage drop through the circuit to the terminals of winding 4 $= 100-\frac{1}{100}\,(I_1Z_1+I_7Z_5) = 100$

$-\frac{1}{100}(49.9-j998)\ (.14+j4)+(9-j167)\ (.125+j12) = 40-j1.47.$

The voltage at the terminals of winding 4 $= \frac{\sqrt{\overline{40}^2+\overline{1.47}^2}}{100} \times 6600$ $= 2640$ volts.

• Example D

Determination of the equivalent impedance of a Delta-Zigzag transformer to a balanced three-phase load. This example shows the use of the theory of the multiple winding transformer for the derivation of the general impedance relations in a circuit involving interphase connections. Assume a delta-zigzag transformer as shown in Fig. 13 with windings of the voltages indicated thereon. If the winding current of the delta-connected winding is I, the winding current of the zigzag winding is $\left(\frac{I}{\sqrt{3}}\right)$ since the line kva must be the same for both windings, that is:

$$\sqrt{3} \times E\,(\sqrt{3}\,I) = \sqrt{3} \times (3E) \times \frac{I}{\sqrt{3}}$$

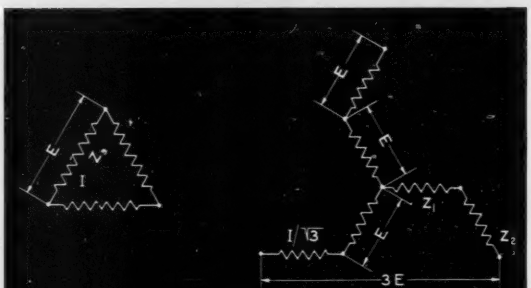


Fig. 13

Let the impedance of each individual winding be represented by Z_1, Z_2, and Z_3 when the impedances are separated into their components according to the theory of three-winding transformers. Let Z_3 be the impedance of the delta-connected winding and Z_1 and Z_2 the impedances of the inside and outside sections of the zigzag winding. Let the total impedance referred to one phase of the primary be Z_e.

Since the sum of the impedance volt amperes for each separate winding is equal to the total equivalent impedance kva:

$$I^2Z_e = I^2Z_3 + \left(\frac{I}{\sqrt{3}}\right)^2 (Z_1+Z_2)$$

$$(11) \text{ or } Z_e = Z_3 + \tfrac{1}{3}(Z_1+Z_2)$$

Let Z_a = the impedance measured on one leg of the transformer between the delta winding carrying I amperes and with the two parts of the zigzag winding on that leg connected in series (so their ampere turns add) and short circuited.

Under this condition each half of the zigzag winding will carry $\frac{I}{2}$ amperes.

Then $I^2 Z_a = I^2 Z_3 + (\frac{I}{2})^2(Z_1+Z_2)$

(12) $Z_a = Z_3 + \frac{1}{4}(Z_1 + Z_2)$

Let Z_b = the impedance measured between one part of the zigzag winding with the other part on the same leg shorted.

That is (13) $Z_b = Z_1 + Z_2$

(14) $Z_a = Z_3 + \frac{1}{4} Z_b$ Substituting from equation (13) in (12)

(15) $Z_3 = Z_a - \frac{1}{4} Z_b$ Solving equation (14) for Z_3

(16) $Z_e = Z_3 + \frac{1}{3}(Z_1+Z_2)$ equation (11).

(17) $Z_e = Z_a - \frac{1}{4} Z_b + \frac{1}{3} Z_b$ Substituting equation (15) and (13) in (16)

(18) $Z_e = Z_a + 1/12\, Z_b$ From equation (17) (collecting terms)

Note that in the last equation if the impedances are expressed in ohms that Z_e, Z_a, and Z_b must be referred to the same voltage. If the impedances are expressed in per cent, Z_e, Z_a, and Z_b must be based on the same kva.

The relation for the impedance of a star-zigzag transformer is exactly the same as is evident by assuming the delta winding connected in star. Other circuits involving interphase connections can be solved in similar fashion using the equations and theory of the multiple winding transformer.

• Limits of Application

The application of the theory of multiple winding transformers to more complicated problems involves the same fundamental principles as its application to the simpler ones demonstrated. It applies equally well to auto transformers as to transformers with separate windings. The impedances from which the constants are determined are found by short circuiting one winding and applying voltage on another winding. As in similar electrical circuits, there must be a linear relation between current and voltage. In order that the method apply, either the exciting current must be negligible for all impedance measurements used in the solution or the circuit set up must include links to represent the exciting current path.

When interphase connections are involved, as for example with a zigzag winding, a single winding in the equivalent circuit should represent only a single winding on a single phase carrying a single current. If the circuit is drawn in this manner, the equivalent circuit will correctly represent the actual circuit.

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Photograph Titles

Cover 1

D-C Motor for Continuous Hot Finishing Mill. 5000 hp, 600 volt, 110/250 rpm. *Robert Yarnall Ritchie Photograph.*

Page 5

30,000 kva, 132,000 volt transformer with Tap Changing Under Load Equipment. *Pohlman Photograph.*

Page 6

Pennsylvania Railroad Electric Express Passenger Locomotive. Single-phase, a-c, 1100 volts, 2500 hp.

Page 7

Reading Railroad 500 hp Multiple Passenger Motor Car. Single-phase, 11,000 volts, a-c.

Page 9

Thirty and 50 hp, 3500 rpm Squirrel Cage Induction Motors Driving Centrifugal Pumps in a Water Pumping Station.

Page 14

Single-Pass, 53,700 sq ft, Surface Condenser and 60,000 gpm Circulating Pumps. *Pohlman Photograph.*

Pages 18 and 19

Port Washington Tandem Compound Reheat Turbo-Generator Unit. 80,000 kw, 1800 rpm. *Pohlman Photograph.*

Page 22

One Three Pole, 138 kv, 1,500,000 kva Interrupting Capacity Oil-Circuit Breaker. *Pohlman Photograph.*

Page 30

Three 30,000 kva, 132,000 volt Transformers with Tap Changing Under Load Equipment. *Pohlman Photograph.*

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On account of the great interest in the dramatized industrial photographs published in the March issue of the Allis-Chalmers Electrical Review, arrangements have been made to furnish one engraver's full-size print, suitable for framing, of any photograph illustrated in the March issue or this present issue. The request must be made on company stationery, and the offer expires July 15, 1937. Address Allis-Chalmers Electrical Review, Milwaukee, Wis.

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